UNCLASSIFIED

STR-16-3

AD 200 803

AD 200 803

REGRADED UNCLASSIFIED ORDER SEC
ARMY BY TAG PER J204313.

CLASSIFICATION
(canceled) [redacted] UNCLASSIFIED
By authority of James H. Douglas
Sec'y of Defense ltr dated Aug 2, 1960 JR 6/22/66

[redacted] UNCLASSIFIED

SUMMARY TECHNICAL REPORT

OF THE

NATIONAL DEFENSE RESEARCH COMMITTEE

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, 50 U. S. C., 31 and 32, as amended. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

This volume is classified RESTRICTED in accordance with security regulations of the War and Navy Departments because certain chapters contain material which was RESTRICTED at the date of printing. Other chapters may have had a lower classification or none. The reader is advised to consult the War and Navy agencies listed on the reverse of this page for the current classification of any material.

[redacted]

Manuscript and illustrations for this volume were prepared for publication by the Summary Reports Group of the Columbia University Division of War Research under contract OEMsr-1131 with the Office of Scientific Research and Development. This volume was printed and bound by the Columbia University Press.

Distribution of the Summary Technical Report of NDRC has been made by the War and Navy Departments. Inquiries concerning the availability and distribution of the Summary Technical Report volumes and microfilmed and other reference material should be addressed to the War Department Library, Room 1A-522, The Pentagon, Washington 25, D. C., or to the Office of Naval Research, Navy Department, Attention: Reports and Documents Section, Washington 25, D. C.

Copy No.

11

This volume, like the seventy others of the Summary Technical Report of NDRC, has been written, edited, and printed under great pressure. Inevitably there are errors which have slipped past Division readers and proofreaders. There may be errors of fact not known at time of printing. The author has not been able to follow through his writing to the final page proof.

Please report errors to:

JOINT RESEARCH AND DEVELOPMENT BOARD
PROGRAMS DIVISION (STR ERRATA)
WASHINGTON 25, D. C.

A master errata sheet will be compiled from these reports and sent to recipients of the volume. Your help will make this book more useful to other readers and will be of great value in preparing any revisions.

[redacted]

UNCLASSIFIED

SUMMARY TECHNICAL REPORT OF DIVISION 16, NDRC

VOLUME 3

NON-IMAGE FORMING INFRARED

OFFICE OF SCIENTIFIC RESEARCH AND [redacted] LOPMENT
VANNEVAR BUSH, DIRECTOR [redacted]

NATIONAL DEFENSE RESEARCH CO [redacted] TEE
JAMES B. CONANT, CHAIRMAN [redacted]

DIVISION 16
GEORGE R. HARRISON, CHIEF [redacted]

WASHINGTON, D. C., 1946

[redacted]

UNCLASSIFIED

Classification upgraded to [redacted]
in accordance with Ltr. AFMPP, 2/9/49
Col. M.D. Burnside, Chief, Plans, Programs and Policy Division
R.H.B.

NATIONAL DEFENSE RESEARCH COMMITTEE

James B. Conant, *Chairman*

Richard C. Tolman, *Vice Chairman*

Roger Adams	Army Representative[1]
Frank B. Jewett	Navy Representative[2]
Karl T. Compton	Commissioner of Patents[3]

Irvin Stewart, *Executive Secretary*

[1] *Army representatives in order of service:*

Maj. Gen. G. V. Strong	Col. L. A. Denson
Maj. Gen. R. C. Moore	Col. P. R. Faymonville
Maj. Gen. C. C. Williams	Brig. Gen. E. A. Regnier
Brig. Gen. W. A. Wood, Jr.	Col. M. M. Irvine
Col. E. A. Routheau	

[2] *Navy representatives in order of service:*

Rear Adm. H. G. Bowen	Rear Adm. J. A. Furer
Capt. Lybrand P. Smith	Rear Adm. A. H. Van Keuren
Commodore H. A. Schade	

[3] *Commissioners of Patents in order of service:*

Conway P. Coe	Casper W. Ooms

NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

UNCLASSIFIED [redacted]

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC; account must be taken of the monographs and available reports published elsewhere.

Division 16 carried out a broad program in the fields of light and optics. Among the studies undertaken were a number involving the principles and techniques of camouflage, and perhaps the outstanding success achieved in this field was the development of the "black widow" finish for night-flying aircraft. Significant improvements were made in aerial mapping and photography. Devices depending on the use of infrared light were developed for the detection of enemy craft, the recognition of friendly ones, and for intercommunication by voice and code. The sniperscope, using image-forming infrared rays, was a spectacular weapon which enabled our troops to fire accurately on an enemy 100 yards away in utter darkness.

The Division 16 Summary Technical Report, prepared under the direction of the Division Chief, George R. Harrison, describes the technical achievements of the Division personnel and its contractors, and is a record of their skill, integrity and loyal cooperation. To all of them, we extend our grateful praise.

VANNEVAR BUSH, Director
Office of Scientific Research and Development
J. B. CONANT, Chairman
National Defense Research Committee

[redacted] **UNCLASSIFIED**

FOREWORD

At the time of its formation late in 1942, Division 16, the Optics Division of NDRC, was assigned both the general task of stimulating and supervising OSRD research in optics and the immediate problem of overseeing a large number of contracts which had previously been initiated by the Instruments Section. Inasmuch as the new Division consisted to a large extent of personnel associated with the Instruments Section during 1940 and 1941, the reorganization involved few important changes.

The present Summary Technical Report describes the accomplishments of both Division 16 and Section D–3, and covers the principal developments in optics made in America during World War II. This report should be considered as intermediate in character between the detailed contractors' reports of Division 16, to which reference is frequently made herein which are complete scientific reports of the investigations carried on, and the historical volume entitled *Optics and Applied Physics in World War II,* which presents in less technical form the accomplishments of the Division and its contractors, and assigns credit to those who took part.

The contents of the present volume demonstrate impressively the great contribution made by the optical industry of America and the university optical laboratories to the war effort. While less glamorous than some of the newer fields brought into existence during the war, optics nevertheless made significant contributions which were by no means confined to mere extension or application of optical methods or apparatus previously in use. The stress of the emergency produced many new optical developments, and the genesis of a large proportion of these will be found recorded in the following pages.

The science of optics and the optical industry have both benefited greatly by the intensive research which took place during the war. Many of the new devices developed under emergency conditions have contributed and will contribute more to our fundamental understanding of optics, and many of them will have peacetime applications. New lines along which optical research should be directed have been made apparent. In particular, the infrared field has benefited greatly, and the art of infrared phosphor development and utilization has been elevated to an entirely new level.

Consideration of the developments in optics, as in other fields, emphasizes that, once adequate immediate defense has been insured, more important than having weapons for a possible future war is having available a large body of trained personnel who can step into any breach that occurs and be available to produce the new devices that may be needed.

The Optics Division of NDRC is especially indebted to the chiefs and members of its Sections, whose names are listed at the end of this volume. They have provided the essential leadership, combined with scientific knowledge, without which the work of the Division could not have been planned or completed.

George R. Harrison
Chief, Division 16

[redacted]

PREFACE

THIS VOLUME of the Summary Technical Report of Division 16, NDRC, records the essential features of the scientific and technical developments carried out under the auspices of Section 16.4 for the military use of infrared radiation. The developments described herein are limited to the field of non-image forming infrared equipments, since the image-forming ones are described in Volume 4 of Division 16 STR.

It is the purpose of this volume to furnish for qualified technical personnel of the Armed Services, and for their future civilian scientific and technical collaborators, a condensed objective record of the problems and achievements of the NDRC in this field, with primary emphasis given to the developments completed under the auspices of Section 16.4 from its formation in January 1943 to the termination of experimental work during the autumn of 1945. It is intended as an outline of the principal achievements and a guide to the more comprehensive accounts contained in the contractors' reports listed in the bibliography.

Some of the earlier work carried out in this field under sections D–3 and D–4, NDRC, which formed a partial basis for the later developments described herein, and also certain related, subsidiary developments made under Section 16.4 are mentioned only in passing as background material. Detailed accounts of these may be found if they should be wanted in the bibliographical references. Certain infrared components closely related to those developed by Section 16.4 and employed in military equipments by other divisions, for example, the heat-homing missiles developed by Division 5, have been left for treatment in the Summary Technical Report volumes of those divisions. In other instances brief descriptions of similar or related components or equipments developed in the United States under other than NDRC auspices, by the British, or by the enemy, are given for comparative purposes. Such accounts have been kept to a minimum, however, in accordance with the basic premise that the report of each section of NDRC should reflect essentially only the developments for which that section was primarily responsible.

For military purposes, infrared radiation may be divided into near infrared [NIR] extending from the visible region to a wavelength of about 5.5 microns, and far infrared [FIR], extending from 5 to 15 microns in wavelength. Because of the radiation-transmission properties of long paths through the atmosphere as well as the characteristics of the only near infrared radiation detectors which were available until the last phases of World War II, the wavelength regions actually utilized extended only from the visible region to about 1.5 microns in the near infrared region, and essentially from 8.5 to 13 microns in the far infrared region.

Generally speaking, the principal difference between the systems used in the near and far infrared regions lies in the fact that most near infrared devices require the use of a special source of near infrared radiation directed toward the receiver, whereas the target itself is a self-luminous source for the far infrared devices. The near infrared systems employ a photoelectric or photoconductive radiation detector having selective spectral response characteristics, while the far infrared devices utilize a detector which absorbs, non-selectively at all wavelengths, the emitted radiant energy as heat.

On account of these differences, this volume may be regarded as having four fairly well-defined parts. The first three chapters describe the characteristics of the three essential optical components—sources, filters, and detectors—of non-image-forming systems working in the near infrared region. Chapters 4 to 7, inclusive, describe the general construction, properties, and military applications of such systems for communication by voice and by code, recognition and identification, determination of the range and direction of targets, and indication of the position of a glider with respect to that of its tow plane. The generalized photometric nomenclature outlined in OSRD Report 1585, which is attached as an appendix to this volume, is used throughout these chapters. This terminology was developed for this spectral region by Section 16.4 and was adopted by the Combined Communications Board of the Combined Chiefs of Staffs representing both the United States and Great Britain.

Chapter 8 outlines the development and characteristics of several different kinds of thermal detectors for far infrared radiation. In Chapter 9 are described the construction, characteristics, and military applications of far infrared receiving equipments employing such detectors for the detection of personnel, vehicles, marine craft, military matériel, factories, power plants, etc., for the determination of range and direction of marine craft, for the thermal mapping of terrain from aircraft, and for the guidance to their targets of certain heat-sensitive, target-seeking missiles.

In the preparation of this volume, emphasis has

been given to the properties of the fundamental components, to the types of possible military applications and to the characteristics of the equipments developed for these applications. It is felt that this type of treatment will give the qualified technical reader a clear view of the present technical status of the development and use of such components and equipments and will provide a definite point from which further developments, some of which are proposed herein, may stem without duplication of past effort. A detailed account of the steps taken in these developments and of the methods of construction of the various components and systems sufficient to permit their reproduction has been avoided.

It is appropriate at this place to acknowledge the contribution of the different contracting organizations and of the individual research personnel and to extend to them the appreciation of Section 16.4, NDRC, for their loyal cooperation in carrying out the scientific and technical developments of the integrated program of Section 16.4 described herein. Following is a list of the research personnel who contributed significantly to the outstanding achievements of each contract. It is hoped that no names have been inadvertently omitted.

University of California OEMsr-1073
Harvey E. White, Technical Representative;
Alfred Einarsson, P. M. Harris, Charles G. Miller

Farnsworth Television and Radio Corporation OEMsr-1094
Madison Cawein, Technical Representative;
C. C. Larson, Alfred Roman, H. Salinger

General Electric Company OEMsr-1322
I. F. Kinnard, Technical Representative;
J. J. Fitz Patrick, C. W. Hewlett, H. T. Wrobel

Harvard University OEMsr-60
E. L. Chaffee, Technical Representative;
F. G. Blake, Jr., C. P. Butler, A. C. Grant, G. L. Harvey, J. R. Hooper, Jr., N. C. Jamison, R. A. Mack, J. D. Strong, J. L. Winget

Johns Hopkins University OEMsr-610
A. H. Pfund, Technical Representative;
W. G. Fastie

Massachusetts Institute of Technology NDCrc-180
A. C. Bemis, Technical Representative;
Willard E. Buck, Ernest B. Dane, A. W. Friend, Roy W. Prince

Massachusetts Institute of Technology OEMsr-561
A. R. von Hippel, Technical Representative;
E. S. Rittner, J. H. Shulman

Massachusetts Institute of Technology OEMsr-576
Hans Mueller, Technical Representative;
Elias Burstein, Norman J. Oliver

Massachusetts Institute of Technology OEMsr-1036
A. R. von Hippel, Technical Representative;
F. G. Chesley, H. S. Denmark, E. S. Rittner, P. B. Ulin

Massachusetts Institute of Technology OEMsr-1147
A. C. Bemis, Technical Representative;
Louis Harris

University of Michigan NDCrc-185
E. F. Barker, Technical Representative;
J. G. Black, R. W. Engstrom, A. Fairbanks, P. H. Geiger, W. L. Hole, L. N. Holland, C. V. Kent, T. R. Kohler, O. G. Koppius, W. W. McCormick, G. A. Van Lear, Jr.

University of Michigan OEMsr-1132
E. F. Barker, Technical Representative;
L. W. Gildart

Northwestern University OEMsr-235
B. J. Spence, Technical Representative;
R. J. Cashman

Northwestern University OEMsr-990
B. J. Spence, Technical Representative;
W. S. Huxford, E. W. Lothrop, R. L. Osborn, J. R. Platt, H. S. Snyder, W. R. Wilson

Northwestern University OEMsr-1391
B. J. Spence, Technical Representative;
R. W. Hummer

Ohio State University OEMsr-987
Wallace R. Brode, Technical Representative;
E. S. Hodge, R. T. Morris, E. E. Pickett, J. H. Shenk

Ohio State University OEMsr-1168
Harald H. Nielsen, Technical Representative;
E. E. Bell, A. H. Nielsen

Polaroid Corporation OEMsr-1085
E. H. Land, Technical Representative;
W. F. Amon, Jr., E. R. Blout, Ridgley D. Shepherd, Jr., Alexander Thomas

Radio Corporation of America OEMsr-1486
Dayton Ulrey, Technical Representative;
R. W. Engstrom, A. C. Glover

V-M Corporation OEMsr-1460
F. Smardo, Technical Representative

Western Electric Company OEMsr-636
J. A. Becker, Technical Representative;
W. H. Brattain, H. Christensen, L. M. Ilgenfritz, J. B. Johnson, J. B. Kelly, R. W. Ketchledge, J. J. Kleimack, W. A. MacNair, H. R. Moore, N. G. Wade

Western Electric Company OEMsr-1098
J. A. Becker, Technical Representative;
W. H. Brattain, H. Christensen, L. M. Ilgenfritz, H. R. Moore

Western Electric Company OEMsr-1231
G. K. Teal, Technical Representative;
E. F. Kingsbury, A. W. Treptow

Western Electric Company OEMsr–1267
R. C. Mathes, Technical Representative;
E. Bruce, W. Herriott, E. F. Kingsbury
Western Union Telegraph Company OEMsr–984
H. P. Corwith, E. C. Homer, Technical Representatives;
W. D. Buckingham, C. R. Deibert, H. L. Smith

It is also a distinct pleasure for the editor to acknowledge the indebtedness of Section 16.4 to those individuals whose painstaking devotion to a laborious task made possible the creation of this record. These include Dr. Winston L. Hole, author of Chapters 1 and 6, and an invaluable critic and assistant in the overall layout and editing of the volume; Dr. Richard C. Lord, author of Chapter 2, who participated in the initial planning of the volume and assisted in the editing of some of the chapters; Dr. John R. Platt, author of Chapters 3, 4, and 5; Mr. Thomas R. Kohler, author of Chapter 7; Dr. Harald H. Nielsen and Dr. Alvin H. Nielsen, co-authors of Chapters 8 and 9; and Mr. Charles A. Federer, Jr., who cooperated in the copy-editing of the manuscripts and performed general liaison duty between Division 16 and the Summary Reports Group at Columbia University.

Acknowledgment is also made to the different contractors for furnishing the master copies of most of the illustrations, and to the Army and Navy for permission to use certain illustrations.

Finally, the invaluable cooperation of Dr. O. S. Duffendack, Chief of Section 16.4, NDRC, in planning the volume, his helpful suggestions concerning its scope and contents throughout its preparation, and his careful reading of the manuscript are greatly appreciated.

JAMES S. OWENS
Editor

CONTENTS

CHAPTER		PAGE
	Summary of Developments in Infrared Techniques, Components, and Equipments under the Auspices of Section 16.4 NDRC by *O. S. Duffendack*	1
1	Near Infrared Sources by *Winston L. Hole*	9
2	Near Infrared Transmitting Filters by *Richard C. Lord*	45
3	Non-Image-Forming Near Infrared Detecting Devices by *John R. Platt*	55
4	Near Infrared Voice-Code Communication Systems by *John R. Platt*	93
5	Near Infrared Recognition and Code Communication Systems by *John R. Platt*	170
6	Near Infrared Systems for Detecting Range and Direction [IRRAD] by *Winston L. Hole*	200
7	Glider Position Indicator and Cloud Attenuation Meter by *Thomas R. Kohler*	215
8	Far Infrared Detecting Elements by *Harald H. Nielsen* and *Alvin H. Nielsen*	225
9	Far Infrared Receiving Systems for Military Applications by *Alvin H. Nielsen* and *Harald H. Nielsen*	279
	Appendix	363
	Glossary	369
	Bibliography	373
	OSRD Appointees	381
	Contract Numbers	384
	Service Project Numbers	385
	Index	387

SUMMARY OF DEVELOPMENTS IN INFRARED TECHNIQUES, COMPONENTS, AND EQUIPMENTS UNDER THE AUSPICES OF SECTION 16.4, NDRC

By *O. S. Duffendack* [a]

SCOPE AND NATURE OF DEVELOPMENTS

Section 16.4 of the National Defense Research Committee [NDRC] was charged with the development of infrared equipments which do not require the formation of a visual image of the target but reveal the presence of the target by aural signals or by indicated signals on flashing lamps, cathode-ray oscilloscopes, meters, or recorder charts.

The work was divided into two major parts: one part using near infrared radiation, from about 0.8 μ to 1.5 μ, and the other part using far infrared radiation, from about 5 μ to 15 μ. The techniques and apparatus used in the two parts are very different. In the near infrared, it is necessary to use an appropriate source of radiation, and rays from this source are detected by the receiver, either directly along a geometric beam or indirectly after regular or diffuse reflection. With far infrared, the target itself is the source, being self-luminous because of the thermal radiation emitted characteristic of its temperature. In the intermediate infrared from about 1.5 to 5.5 μ, both types of techniques are possible and both were under development at the conclusion of World War II.

Near infrared devices, "Nancy" equipment, were developed for purposes of (a) detecting and locating other installations of Nancy equipment, friendly and enemy planes, etc., (b) ranging, (c) recognition or identification of friendly ships and planes, and (d) communication by voice and by code. The most extensive developments were for ship recognition and for voice and code communication between ships. The range of these equipments in average clear weather is 6.5 to 10 miles; the distance for effective operation decreases rapidly with increasing cloudiness or fog.

Infrared systems were developed primarily for use under military conditions in which it is desirable to maintain radio and radar silence. The transmitters used with near infrared systems, particularly the communication systems, project sharply defined beams of radiation and cannot be detected except by a receiver properly oriented in the beam. When necessary the beam can be restricted to a very small angle and is, moreover, limited to line-of-sight reception. Thus a very high measure of system security is achieved, and message security may be still further enhanced by special conditions of modulation, some of which are briefly indicated in subsequent paragraphs.

Since the far infrared systems utilize only the natural thermal radiation from the target and do not require an auxiliary source, their operation is not self-revealing in any way, at any distance. Far infrared receivers were developed: (a) for the detection and location of personnel, vehicles, tanks, planes, and ships; (b) for ranging; and (c) for the guiding of missiles. The range of the far infrared receivers is from a few hundred yards for personnel to about 12 sea miles for a destroyer in average clear weather. In some of the experiments the range was limited by the horizon because the apparatus was mounted at a relatively low elevation on shipboard. Again the range is drastically reduced by clouds and fog.

Intermediate infrared devices were in the earlier stages of development but showed great promise for use both in the detection of military objects and in communications.

NEAR INFRARED DEVELOPMENTS

Photocells

In order that near infrared equipments of military value could be developed, it was necessary that more sensitive photocells for this region should be obtained. The only photocells of this type available at the beginning of the war were cesium photocells, and these were being manufactured only on a small scale. A few electron multipliers with cesium photocathodes were being made for laboratory use. Section 16.4 instituted two lines of research and development, one to improve the characteristics and production methods for improved electron multipliers and another to develop new types of photo-

[a] Chief, Section 16.4 NDRC; Director, Philips Laboratories, Inc., Irvington, New York.

cells sensitive to infrared radiation. Both lines were fruitful, and the equipments developed profited by the availability of these improved detectors.

Several research and development groups in different laboratories concentrated on the problems involved in improving and producing cells of the Thalofide type, first produced by Case during World War I. The result of these efforts was the development of a very stable thallous sulfide photoconductive cell which was incorporated in several military equipments, such as those indicated for recognition and communication both by voice and by code. The methods for the quantity productions of these cells in two specific types were worked out by two tube manufacturers.

Sources

Besides improved photocells for infrared receivers, it was necessary to develop improved sources of near infrared radiation. These developments proceeded along four lines.

1. Tungsten filament lamps of special design were developed which could be electrically modulated with high efficiency at low frequencies (90 cycles per second) and likewise enabled code signals to be sent at higher speeds than before, up to the limit of the operator at about 30 words per minute.

2. A concentrated-arc projection lamp was developed which proved successful as a source of high intensity and small size. It is especially effective, because of its small size, in projecting beams of very narrow angles by means of mirrors and lenses. This source was used more widely in technical optical applications, such as bore sighting, than in direct military infrared equipments for field use.

3. Microflash lamps were developed in three types, one of high intensity with a flash duration of about 30 μsec; a second, also of high intensity, with a flash duration of about 3 μsec; and a third, especially rugged and long-lived but of less peak intensity, having a flash duration of about 1 μsec, was developed by the General Electric Company with the consultation and advice of the section. Only the third type was adopted as an infrared source in military equipments; it was employed in a ranging apparatus [IRRAD], described later. The second type of lamp was employed in some equipment developed by Section 16.4 for the Ballistics Laboratory at Aberdeen Proving Ground to photograph high-speed shells in flight.

4. With the advice and aid of the section, the Westinghouse Electric Corporation developed an electrically modulated cesium-vapor lamp of high modulation efficiency at voice frequencies. This lamp was developed especially for use in the type E communication system, in which the apex of the cone of radiation at one-half of the beam-center intensity has the angular dimension of 13 degrees, and was in quantity production at the end of the war. Other systems providing still wider angles of communication with this lamp were in an advanced stage of laboratory development at that time.

Filters

Because none of the sources mentioned above emit infrared radiation only, but also emit more or less visible light as well, it was necessary to develop filters to screen out the visible light and transmit only the infrared. Since a sharply defined wavelength limit of visual response does not exist and since no filter could be found which cuts off abruptly at the "end" of the visual range, a series of filters was developed which give varying degrees of visual security with a particular source, as demanded by the operation in which the equipment is used, while maintaining the maximum feasible operating range of the equipment. In general, the greater the visual security is, the lower becomes the percentage transmission of infrared radiation integrated over the range of useful wavelengths for the equipment.

When the war began, infrared transmitting filters of glass were available in several types. Investigation showed that these could not be materially improved in efficiency of transmission, but considerable improvement was made in their ability to withstand mechanical and thermal shocks. Glass filters of special forms, as in the form of Fresnel lenses, were also developed for various military beacons.

Two laboratories worked on the development of plastic infrared transmission filters in the hope that higher percentage transmissions of infrared radiation could be achieved. Both laboratories were successful in doing this; one developed a filter of dyed sheets of polyvinyl alcohol sandwiched between plane glass plates, and the other a dyed melamine formaldehyde plastic, plasticized by an alkyd resin,

which was caused to harden on a glass or transparent plastic supporting plate. Both types of plastic filters were made available in a wide variety of wavelength versus transmission characteristics and both were superior to the glass filters in integrated percentage transmission of infrared radiation with comparable visual security. They were adopted for use in several military equipments and were available in considerable quantities at the end of the war.

NANCY-TYPE MILITARY EQUIPMENTS

Glider Position Indicator

Several military equipments employing near infrared radiation were developed to the point of demonstrating working laboratory models to the Armed Services but were not brought to quantity production. One of these was the *glider-position indicator* [GPI], which had for its purpose the indication of the position of a glider with reference to its tow plane so that the glider pilot could keep the glider in its proper position while flying through fog so dense the tow plane could not be seen. Infrared radiation was prescribed instead of visible light only for security reasons, the transmission of near infrared radiation through fog being only slightly better than that of visible light. The transmitter utilized a tungsten lamp and infrared filter, and a thallous sulfide cell was used in the receiver. Satisfactory operation was demonstrated in flight tests, with an estimated range for the laboratory model of about 200 feet through the densest clouds likely to be encountered.

Life-Raft Search Equipment

Another device demonstrated but not put into production was designed to locate life rafts or small boats adrift at sea. Each such raft or boat would be equipped with a set of retrodirective reflectors. A search plane would be equipped with a scanning infrared transmitter and receiver and would fly over the sea and scan a strip of its surface with an infrared beam. When some of the radiation from this transmitter is reflected back to a tuned receiver on the plane, a signal is presented. By means of a rotating shutter the transmitted beam is modulated at the frequency of the tuned receiver, and thus false signals are avoided. An incandescent tungsten lamp is used in the transmitter, and a thallous sulfide cell in the receiver. The equipment is not effective for search in bright daylight; a night range exceeding 2 miles was demonstrated with the unit land-based, and this could probably be met or exceeded under favorable weather conditions in an automatic airborne model.

Enemy Infrared Installation Locator (Japir)

A third device in this class was designed to detect the use of and to locate the approximate position of enemy near infrared equipments. It consists of a near infrared receiver which is to be mounted on a search plane. Either unmodulated radiation, voice or code modulated signals can be detected. When a signal is received the operator knows that a source of near infrared radiation is in operation and is located in the direction indicated by the receiver. The range of this device depends upon the strength of the infrared source and on the weather conditions. As an example, a source consisting of a 240-watt tungsten lamp enclosed in a red glass H globe was detected at a distance of two miles.

Irrad

A near infrared detection and ranging system constitutes a fourth device not put in quantity production but transferred to Navy auspices for further specialized development before the end of the war. In this system, known as IRRAD, infrared techniques are applied to the basic principles utilized in radar. An infrared pulse of about 1 μsec, emitted from a microflash source, is detected and amplified after being reflected from a highly efficient retrodirective reflector target. The signal is presented on a cathode-ray tube. A narrow-angle transmitted beam is used and is scanned over the search area so that a target may be accurately located in azimuth and elevation, while the time delay between the initial pulse and the received signal is accurately translated into target range. An electron multiplier with cesium photocathode is used to detect and preamplify the signal pulse. A single 2-inch target was detected at 4,000 yards with the laboratory model; it is estimated that the range in clear weather may be extended to 10,000 yards for an array of six reflectors so oriented as to present a uniformly good target around the en-

tire horizon. Diffusely reflecting objects such as ships, trees, buildings, etc., can also be detected, but only at ranges too short to be of military value.

Recognition and Code Communication System, Type D

This system was developed for the U. S. Navy as an aid in station keeping and communication in convoys and task forces. One or two modulated sources of near infrared radiation are mounted on board each ship in such a way as to cover an angle of 360 degrees in the horizontal plane and about ± 25 degrees in the vertical plane. One or two receivers with amplifiers sharply tuned are mounted on each ship on stabilized oscillating stands in such a way that two receivers can automatically scan through 360 degrees in the horizontal plane. A thallous sulfide cell mounted at the focus of a parabolic mirror can receive radiation in a cone with apex angle of 11 degrees. The vertical-angle coverage of the transmitters is large enough so that they do not need to be mounted on stabilized platforms. The transmitter can be made to send out a repeated identification signal by an automatic keyer, or to send code messages up to 30 words per minute, limited only by the skill of the operator, by manual operation. The receiver presents the signals by means of small flashing lamps, headphones, or a loudspeaker. With a 500-watt source in very clear weather, a range of about 9 miles has been successfully demonstrated; the average clear weather range is about 6.5 miles. The visual security distance is 400 to 1,200 feet, depending on the choice of filter. Type D equipment was in quantity production at the end of the war.

A related equipment for plane-to-plane identification had also reached the stage of advanced laboratory development at this time.

Voice (and Code) Communication Systems

At the request of the Bureau of Ships, Section 16.4 undertook the development of a voice and code communication system over wide-angle beams of near infrared radiation. The transmitter of the final model, type E, consists of an electrically modulated cesium lamp mounted in a parabolic mirror. This transmitter produces a conical beam of circular cross section, with an apex angle of about 13 degrees. Plastic infrared transmission filters are used which provide security of 400 yards maximum visual range. The source and receiver are combined into one unit called a transceiver. The receiver consists of a thallous sulfide photocell mounted on the axis of a parabolic mirror. Its angle of view is approximately conical, with apex angle of about 19 degrees between the points of half-peak response. The angles covered by transmitter and receiver are wide enough so that it is unnecessary to mount the transceiver on a stabilized platform on board ship. This equipment has ranges of approximately 6.5 miles for voice and 9 miles for code in average clear weather. At the end of the war, this system had just gone into quantity production.

Similar systems were developed for aircraft, to be used either from plane to plane or from plane to ground. These differ from the type E system mainly in being reduced in size, weight, and power requirement to adapt them for aircraft installations. These are wide-angle equipments of shorter range than type E and are intended primarily for use in communication between planes flying in formation and in airborne troop landing operations.

For plane-to-ground communication, a different system, type W, was developed to serve as the ground unit in airborne troop landing operations. Two of these units also constitute a portable, lightweight communication system for use between land or ship stations. The source consists of a tungsten filament lamp mounted in an ellipsoidal reflector. The radiation is mechanically modulated by a vibrating mirror. The receiver uses a thallous sulfide cell and is patterned after the receiver of the type E system. The equipment is portable and can be operated from a small portable storage battery. The entire equipment weighs only 18 pounds and can be carried down from a plane by a paratrooper. The range for a pair of these units is about 1.5 to 3 miles in average clear weather, depending on the angular width selected for the transmitted beam. Quantity procurement was being planned at the end of the war but had not been actually initiated.

Two other voice communication equipments were developed and demonstrated but were not put into quantity production. One of these employs plane polarized infrared radiation which passes through a photoelastic shutter and is modulated and transformed into circularly polarized radiation. Only a receiver having a properly oriented polarizing screen

can receive the signals, although the apparently unmodulated radiation may be detected, for example, by an infrared telescope. The final laboratory model of this equipment has a range of about 4 miles in average clear weather and provides very high security against interception of messages. The device is necessarily more complicated and less efficient than other systems described here.

The other equipment was originally developed in France and was reconstructed here by a French naval officer. Its receiver is conventional, but the transmitter employs a special source consisting of a glow discharge lamp mounted at the focus of a parabolic reflector. This lamp has high modulating efficiency at frequencies of 100 or 200 kilocycles, and so a high-frequency carrier wave modulated by the voice is employed. Such a system can be constructed so that the message cannot be received except by a receiver tuned to the frequency of the carrier wave. In this way greater security against interception of messages can be attained and several different frequency channels of communication can be provided.

FAR INFRARED DEVELOPMENTS

Since the far infrared equipments of current military interest do not require auxiliary sources or filters, fundamental development of components was limited to new or improved detectors and optical components for receiving and utilizing self-emitted thermal radiations.

Improved methods were developed for producing various types of thermal detectors having faster response and lower threshold detectable energy limits than before the war. These include thermopiles, evaporated metal-strip bolometers, and thermistor bolometers of various types. The thermistor bolometers experienced the greatest improvement and were most widely used in the military equipments developed by this and other NDRC sections. In addition, a considerable improvement in the performance of equipments resulted from fundamental studies on scanning systems and optical components for infrared receivers, including mirrors, Schmidt plates, transmitting cover or window materials, and protective coatings.

One contract of the section also made extensive studies, in cooperation with the Armed Services, on the comparative characteristics of many different detectors and receivers, both domestic and foreign. Consultation, evaluation, and assistance to military agencies and other Office of Scientific Research and Development [OSRD] divisions on matters pertaining to far infrared components and techniques constituted an important phase of the section's program.

CASPAR-TYPE MILITARY EQUIPMENTS

All of the far infrared equipments developed employ "Caspar" technique, that is, they operate on radiation emitted by the target acting as a self-emitting infrared source. Two of these equipments were designed especially to detect ships, the *portable ship detector* [PSD] and the *stabilized ship detector* [SSD].

The PSD consists of a receiver head mounted on a tripod and appropriate power supplies, amplifiers, and signal indicator. The receiver head oscillates so as to scan periodically through a small angle along the horizon. When a ship lies within the angle scanned, an aural signal is given. The head may be turned by hand so as to scan a wide area of the sea in successive steps. This equipment has a range in average clear weather of 4,000 to 10,000 yards, depending on the size of the target ship. It was superseded by the SSD.

The SSD was developed to be mounted on a stabilizing platform. It detects the presence of a ship within its range and gives the bearing with an error of less than ¼ degree. The head oscillates through an angle which can be quickly set or changed from a few degrees up to 180 degrees. Radiation from the target ship or ships falling first on one and then on the other of a pair of thermistor strip bolometers produces signals which are recorded on a chart in such a way that the bearings of all the ships in the field of the receiver can be quickly read. Relative movements of the target ships with respect to the ship bearing the SSD can be followed from the record on the chart. The SSD has a range in average clear weather varying from 4,000 to 25,000 yards, depending upon the size of the target ship. A quantity-production program was being set up when the war ended.

The SSD lends itself advantageously to operation in combination with other equipments. A combination of the SSD with a radar set was planned, but the end of the war terminated its development before completion. The idea was to detect the target

ship and determine its bearing with the SSD in complete secrecy, while maintaining radar silence, and then to determine its range by a brief operation of the radar unit. Another possible combination consists of the SSD and a narrow-angle voice or code communication system. In this combination the SSD would be used to train and direct the beams of the communication system. These would train simultaneously so that when the SSD detected a friendly ship the beam of the communication equipment would face upon it, and so contact could be immediately established and maintained through an automatic lock-on system without searching with the transmitted beam of the communication system. This arrangement would permit the use of very narrow-angle beams and would thus greatly increase the security of communications.

The *portable NAN detector* [PND] was developed originally to detect personnel but was found applicable for the detection of tanks, motor vehicles, ships, small boats, and buildings as well. In its simplest form it is a completely self-contained unit operating from dry batteries. This model weighs less than 10 pounds exclusive of mounting tripod and has a range in average clear weather of 500 yards for a man, about 2,500 yards for a small tank and several thousand yards for a ship. The detector is a pair of strip thermistor bolometers mounted in a cell with a rock salt or silver chloride window at the focus of a 7-inch parabolic mirror. The signal is presented by means of headphones. A production model called Penrod was developed but a very limited number had been made by the end of the war. One laboratory model PND was used to guard the crossing of a river in Germany. It was set up to give warning in case any person or object crossed through its cone of observation. Similar uses for this device were proposed, such as to give warning of the approach of enemy troops or tanks along a road or passageway within the cone of observation of the PND and to warn of enemy troops coming in toward shore on a beachhead at night.

Outgrowths of the PND were the *scanning NAN detector* [SND] and the *thermal map recorder* [TMR]. The SND has a scanning head which causes images of objects in the field of view to sweep across first one then another thermistor bolometer. The signals are recorded on a chart as small vertical lines. The thermal map recorder is similar to the SND in general features but is a more refined instrument and presents a better record, like that of the SSD, consisting of small dots at points along a line corresponding to the relative positions of the targets. The chart advances a small amount between two sweeps of the scanning head so that the signals from a given target at rest form a dotted line along the length of the record strip. Motion of a target is indicated by a slanting or curved dotted line formed by its signals.

These instruments construct a thermal map of the area scanned by them if they are carried forward by a plane. Any object differing in indicated temperature from its surroundings gives a signal and thus buildings, trees, vehicles, roads, creeks, and banks of rivers or shore lines are charted. Some of these give stronger signals than others and the gain of the amplifier can be set so as to eliminate the weaker signals. Thus it is possible under favorable conditions to record signals from tanks on a road and not the road or trees along side it. Because of the unsteady motion of a plane, it was found necessary to mount the instrument on a stabilized platform in order to get a consistent thermal map. Plans were under consideration to do this when the war ended. The ranges of the SND and of the TMR are about the same as those of the PND. The war ended before quantity production of these instruments was achieved.

Another equipment under development for the Bureau of Aeronautics, USN, is known as type L. It was designed to be used on a drone and was intended to send signals by means of a radio link to the plane controlling the flight of the drone. The signals were to indicate the angle between the line of flight of the drone and a line from the drone to the target and thus permit the operator in the controlling plane to direct the drone in a collision course. When the war ended the development had reached the stage of demonstrating the detection of a target ship and presenting its signals on a cathode-ray oscilloscope while the equipment was borne by an airplane.

Other Developments

Space does not permit discussion of other applications of bolometers with which Section 16.4 assisted by advice and counsel and by making available developments on bolometers carried out under its auspices. These applications are reported else-

where and can be only briefly enumerated here. Bolometers were applied, for example, in heat-homing bombs, bombsight with angular rate release, and airplane detecting equipments developed under the auspices of other sections of NDRC.

DEVELOPMENTS IN THE INTERMEDIATE INFRARED REGION

Lead sulfide cells had been developed to the point at which they were about ready for quantity production when the war ended. Two types were developed, one operating at ambient temperatures and the other at reduced temperatures resulting from cooling with solid CO_2 (dry ice). A reservoir was provided which would hold enough dry ice to permit operation for several hours without refilling. These cells are sensitive to longer wavelength radiation than are thallous sulfide cells and have better frequency response characteristics. It is likely that they would have been widely adopted to provide additional communication channels at wavelengths greater than 1.5 μ had the war continued another year. Because of their sensitivity to longer wavelengths, filters providing greater visual security for a given source could be used with lead sulfide cells than with thallous sulfide cells. Tests on other types of photoconductive materials were in progress when the war ended.

Since the lead sulfide cell is sensitive to infrared radiation of wavelengths up to about 3.5 μ, it can be used to detect objects at prevailing outdoor temperatures. Hence, Caspar-type receivers with lead sulfide cells are also possible. One such was constructed and some tests were made on the detection of ships. The ranges were less than those of the instruments using bolometers, but considerable improvement may be anticipated from further work.

Chapter 1

NEAR INFRARED SOURCES

By *Winston L. Hole*

1.1 INTRODUCTION

The purpose of this chapter is to describe the nature and characteristics of the *near infrared* [NIR] sources which have been found most suitable for use in non-image-forming applications, including specifically equipments and military systems which will be described in greater detail in Chapters 4, 5, 6, and 7. It includes a description of certain types of the incandescent tungsten lamps in new or improved adaptations and, in addition, a description of several other sources newly developed under NDRC or Navy auspices which contributed to the NDRC near infrared program.

1.1.1 Types of Sources

The near infrared sources described in this chapter fall within two main categories, namely, incandescent tungsten lamps and special gaseous discharge lamps. The treatment of standard incandescent tungsten lamp types listed in the bulletins of commercial manufacturers is limited principally to an enumeration of their physical characteristics and a brief description of the radiation characteristics of the beacons or transmitters in which they have been used. One special incandescent lamp developed by the General Electric Company at the request of NDRC Section 16.4 and one rather novel adaptation in the use of an already standardized type of lamp are described in somewhat greater detail in Section 1.2.2. The construction, mode of operation, and general radiation characteristics of the special gaseous discharge lamps developed under the auspices of this section are treated still more fully, and a similar treatment, except for the details of construction, is given for the cesium vapor lamp, developed under a Navy (BuShips) contract with the Westinghouse Electric Corporation. This lamp was extensively used in the military equipment developed by one contract of this section.

1.1.2 Types of Applications

The near infrared sources described in this chapter have been used in conjunction with appropriate optical systems, infrared transmitting filters, and radiation detectors in the development of military equipments under contracts administered by NDRC Section 16.4. The various applications include voice-code communication systems, recognition and code communication systems, a position-indicating system for gliders, a system for the detection of retrodirective triple-mirror reflectors, and systems for the detection and ranging either of retrodirective triple-mirror reflectors or of large, diffusely reflecting targets such as ships. Another important application primarily involving visible rather than infrared radiation lies in the ballistic photography of high-speed projectiles with a gas-filled, high-intensity flash lamp especially developed to provide a flash duration short enough for this purpose. A description of other components and of the complete systems is given in subsequent chapters. More detailed information on each subject is given in the Bibliography.

1.1.3 Nomenclature System for Near Infrared Photometry

The free interchange of ideas and comparison of results between various laboratories concerned with near infrared developments was at first hampered by the lack of an adequate system of nomenclature and units for near infrared photometry. The early recognition of the need in this field for a uniform basis of testing and comparison led to the proposal of a system which was subsequently approved and adopted for official use by the Combined Communications Board of the Combined Chiefs of Staff. The officially approved report [1] in which this system is presented in schematic version is reproduced in the Appendix. Its terminology is generally followed

throughout the near infrared portions of the volume whenever the contribution of wavelengths beyond the visible must be taken into account or when a radiation detector having spectral response characteristics different from those of the eye is referred to.

This system, sometimes referred to as the *hololumen* system, has the advantages of being very closely associated with an established system of visual photometry and of using the total radiation from the universally available incandescent tungsten lamp, properly standardized at the color temperature of 2848 K, as a standard of comparison for taking cognizance of the near infrared radiation component from this and other types of source with respect to any detector of visible and near infrared radiation.

Although in practice certain difficulties and objections to the system have arisen, its creation and adoption have been amply justified in terms of scientific as well as purely practical results. It has helped to eliminate some of the approximations and guesswork which, in the absence of such a system, previously existed in the field of near infrared photometry. It further constitutes a valuable step toward a badly needed fundamental system of measurement and nomenclature for general use in connection with selective radiation sources, filters, and detectors.

An outstanding example of its potential value was demonstrated by four cooperating laboratories under the sponsorship of NDRC Section 16.4. Each laboratory was provided with a set of primary standards consisting of incandescent tungsten lamps, infrared transmitting filters, and cesium-surface vacuum phototubes. The color temperature and intensity of the lamps, the *effective holotransmission* [ehT] values of the filters, and the spectral response characteristics and responsivities of the phototubes were initially calibrated and intercompared at a single laboratory. On the basis of these results, and through preliminary selection of closely matched units, correction factors not exceeding 10 per cent were determined for each combination of source, filter, and detector within the group of primary standards assigned to each laboratory. Subsequently it became possible for the first time for one laboratory to duplicate closely the results of another in measuring the characteristics of a given source, with a considerable saving in the time and effort previously devoted to the explanation or elimination of conflicting results.

It is assumed that the reader is familiar with the basic principles of optics and photometry and with the fundamental vocabulary used by textbooks in these fields. More specialized terminology which has been found of sufficient value to warrant its adoption within NDRC groups will be defined at appropriate points in this and subsequent chapters.

1.1.4 Methods of Modulation; Modulation Ratio

The successful operation of a non-image-forming system frequently requires that the source be modulated or pulsed in such a way that the radiation emitted by it varies in a regular or periodic manner. In addition it may be necessary to interrupt the modulated radiation, as for code transmission, or to superimpose additional modulation at a substantially different frequency, as for modulated carrier-wave communication systems. Details of these requirements for certain applications, and of the methods developed to meet them, are given in Chapters 4, 5, 6, and 7.

All of the sources described in this chapter are electrically operated, but not all of them can be successfully modulated at the source by electrical means to meet the frequency, waveform, or other requirements of a specific application. Incandescent tungsten lamps, for example, cannot be efficiently modulated even at the middle audio frequencies by direct operation from an a-c source. Every source has certain limitations in this respect. Each must, therefore, be considered separately, (1) as a source of steady radiation which may be modulated by mechanical means after it leaves the source, and (2) as a source of radiation which may be modulated or pulsed directly by the electric power supply from which it is operated. For example, there may be a considerable time lag between the operating current and the corresponding phase of the emitted radiation, as well as a considerable difference between the depth of modulation of the operating current and the resulting radiation. In addition, all wavelengths emitted by a source do not have the same modulation characteristics under identical conditions of operation.

It is evident that a great many details must be given careful consideration in choosing the source

of highest overall efficiency for a particular application. No attempt will be made here to analyze or enumerate all of these factors in relation to waveform, chopper efficiency, power consumption, etc. However, in considering electrically modulated sources, three basic definitions for the case of simple sine wave modulation will be of value.

By "per cent current modulation" is meant

$$\frac{\text{Amplitude of the sine wave modulating current}}{\text{Direct-current operating value without modulation}} \times 100.$$

By "per cent modulation of emitted radiation" is meant

$$\frac{\text{Amplitude of the modulated component of radiant intensity}}{\text{Radiant intensity during operation on unmodulated direct current}} \times 100.$$

By "modulation ratio" is meant

$$\frac{\text{Per cent modulation of emitted radiation}}{\text{Per cent current modulation used for operating the source}} \times 100.$$

Thus a modulation ratio of unity is achieved only if the depth of modulation of the emitted radiation is equal to that of the modulating current. The values of the modulation ratio which may be achieved with a given source are a significant measure of its effectiveness as an electrically modulated radiation source.

1.2 INCANDESCENT TUNGSTEN LAMPS

Because the wavelength of peak spectral radiant intensity lies near one micron for incandescent lamps at about 3000 K, these lamps constitute a valuable and widely used source for near infrared radiation. Their design and detailed characteristics are discussed more fully in the Summary Technical Report of Division 16, Volume 4, Chapter 5. Only those tungsten lamps specifically used in the military equipments developed by Section 16.4 are enumerated in the present chapter, together with a brief description of their mode of application. Other lamps have, of course, been widely used in the laboratories and in test apparatus auxiliary to the equipments described below. The lamps are identified by means of the standard abbreviations used in the technical bulletins and catalogs issued by the commercial lamp manufacturers.

1.2.1 Lamps of Standard Type for Miscellaneous Purposes

COMMUNICATION SYSTEM WITH PHOTOELASTIC SHUTTER [2,3]

A voice communication system utilizing a photoelastic shutter was developed under Contract OEMsr-576 with the Massachusetts Institute of Technology. The shutter consists of a clear glass plate in which a standing elastic wave of constant frequency but variable amplitude is excited by means of one or more quartz crystals electrically driven by a low-power radio transmitter. Plane-polarized radiation impinging on the shutter is rendered elliptically polarized by the photoelastic birefringence resulting from the elastic stresses set up in the shutter. A properly oriented analyzing sheet of infrared polarizing material is needed over the radiation detector to permit reception of the transmitted message. Since, in addition, the intelligence is transmitted only within a rather narrow cone of invisible radiation, the transmitter possesses an exceptionally high degree of security. The infrared polarizing sheets used in both transmitter and receiver were produced by the Polaroid Corporation. The complete communication system and its operating characteristics are described in Chapter 4.

In the first laboratory model, a 420-watt Mazda incandescent aircraft landing lamp (G–25 bulb, C–2 filament, 12 volts, 35 amperes) rated at 10,500 approximate initial lumens was used as the source. It was operated from an a-c line through Variac and transformer controls. Radiation from the filament was focused by an 8-inch diameter, semiprecision parabolic reflector within an area about 1.5 inches square about 20 inches from the source. At this point the radiation passed successively through an infrared polarizing sheet, a Polaroid Corporation infrared transmitting filter, and the photoelastic shutter, each component being 2 inches square. The emerging radiation was then projected by a clear glass lens of 8-inch diameter and 12-inch focal length in a cone subtending approximately 20 degrees. Even when the shutter was operating, the transmitter was completely invisible to the dark-adapted eye at any distance.

In later models the size of the shutter was successfully increased to 4, 6, or 8 inches square and at the same time provision was made for using a more intense source, such as a sealed-beam type tungsten lamp. A wide variety of adjustments in transmitter beam widths, power consumption, etc., thus became possible by correlating the choice of a particular source lamp with other optical components selected for the transmitter. With high-power sources it was necessary to include a water filter or a forced-air cooling system to prevent the thermal destruction of the plastic membrane, infrared polarizing and filter sheets.

A Navy (BuShips) contract for the construction of one or more improved communication systems of this type was later negotiated with White Research Associates, Cambridge, Massachusetts. A final report on this development was not available at the date of this writing.

An Infrared Glider Position Indicator [4]

Equipment for indicating the position of a glider with respect to its tow plane was developed by the University of Michigan under Contract NDCrc-185. A lamp of the photocell-exciter type (T-8 bulb, C-6 filament, 10 volts, 5 amperes, single-contact bayonet base) was used as the radiation source in this equipment. An ammeter and a rheostat control were included in the lamp circuit which was operated from the 12-volt battery of the tow plane.

The center of the lamp filament was located at the focal point of a Bart parabolic mirror of 2-inch focal length and 3-inch diameter. The collimated beam reflected from the parabolic mirror was then reflected successively from two plane mirrors (front-surface-aluminized glass), each of which was vibrated about one of a pair of mutually perpendicular axes in such a way that the projected beam described a Lissajous pattern in space. The transmitter assembly was covered by a clear glass window to which was attached a sheet of Polaroid XR7X25 infrared transmitting filter.

The angle subtended by the projected image of the lamp filament was approximately one degree horizontally by five degrees vertically. By means of the two vibrating mirrors this image was scanned in such a manner as to give fairly uniform coverage over a space field subtending about 20x20 degrees at a repetition frequency of 14 per second. The characteristics of the scanning pattern were fixed by the choice of a 6 to 1 ratio for the frequencies of the two vibrating plane mirrors. The complete system, described more fully in Chapter 7, constituted a rudimentary infrared television system with the radiation pickup and presentation unit located in the glider within the television scene. Because of the space modulation (or scanning) system in which this source was used, and the time-dependent response characteristics of the thallium sulfide cell used as the radiation detector, information on the beam candlepower and similar characteristics for this source is not easily related to the operating characteristics of the system and is therefore not given here.

Retrodirective Reflector Target Locator [5]

An apparatus for detecting and locating retrodirective reflectors by means of infrared radiation was constructed by the University of Michigan under Contract NDCrc-185. The radiation source was a 300-watt projector-type tungsten lamp (T-10 bulb, C-13 filament, 30 volts, 10 amperes, medium prefocus base) operated from a 24-volt d-c aircraft power supply with a control rheostat. If needed, a 6-volt storage battery could be used to boost the line voltage up to the normal rating for this lamp. A 3-inch, second-surface glass spherical mirror of commercial grade was located on one side of the lamp with its center of curvature at the center of the filament. On the other side of the lamp was a Fresnel-type optical signal lens of $5\frac{3}{8}$-inch diameter and $3\frac{1}{2}$-inch focal length, located with its focal plane at the lamp filament. An image of the filament region, strengthened by the spherical backing mirror and fairly uniform over an approximately square zone subtending a total angular width of about 4 degrees, was projected with this arrangement. The beam candlepower with no filter over the source was approximately 125,000. The angular dimensions of the beam could be increased to approximately 10 degrees square, with a corresponding decrease in beam candlepower by a factor of 6 to 7, by inserting a "beam spreader" of hammered glass treated with clear lacquer. An infrared transmitting filter consisting of two sheets of Polaroid film cemented to a clear glass plate, having a transmission approximately equal to that of XR7X25 material, could be inserted in the beam to provide a high degree of visual security.

Because of the highly accurate retrodirective reflecting property of the triple mirrors which were used as targets, the source and the coaxial cylin-

drical shutter by which the radiation was modulated were designed as compactly as possible and mounted on the axis of the 12-inch reflector which focused the signal flux on the radiation-sensitive element of the receiver. In this respect the equipment was similar to the IRRAD equipment, described in Chapter 6, for detecting and ranging the same type of target.

The cylindrical modulating shutter was driven by a 24-volt d-c governor-controlled motor and produced trapeziform time modulation of the projected flux at 90 cycles. To this shutter was attached a small blower which provided forced air ventilation of the lamp. A separate blower without a shutter could be used interchangeably with the preceding combination when it was desired that the signal flux be modulated by a chopper at the triple-mirror target in order to minimize the effects of atmospheric backscatter. The entire equipment and its performance characteristics are described in Chapter 5.

Portable Hand-Held Infrared Optical Telephone (Type W)[6]

A lightweight infrared voice transmitter-receiver development begun by the University of California under Contract OEMsr–1073 with the direction of Section 16.5 was later transferred to Section 16.4 and successfully completed under these auspices. In the early models a 40-watt, 50-candlepower automobile spotlight bulb was used. A 10-pound, 6-volt portable storage battery would permit nearly two hours of continuous operation, or, if available, an automobile or other large storage battery would permit longer operation without recharging the battery. With this source the angular dimensions of the transmitted beam were approximately 2x3 degrees. In the final models a 4x5-degree beam was obtained through the use of a 100-watt incandescent tungsten source (5.5 volts, 18 amperes, average life only 5 to 10 hours because of operation at about 3400 K) specially constructed for this purpose by the General Electric Company. The period of continuous operation from the portable storage battery is correspondingly reduced to about one hour. A Lucite beam spreader attachment, which widens the transmitted beam to approximately 10x12 degrees, could be inserted when desired. When no filter is included in the transmitter, the beam candlepower is 7,000 to 8,000 for the 4x5-degree beam. But the Lucite beam spreader lowers this to 1,200 to 1,600.

The transmitter is given a high degree of visual security by the insertion of a suitable infrared filter adjacent to its external protecting window. The optimum filter for a particular situation depends upon the beam candlepower being used. Suitable filters were supplied by both the Polaroid Corporation under Contract OEMsr–1085, and Ohio State University under Contract OEMsr–987. The filters for operational tests were chosen so as to limit the range of visibility for a dark-adapted naked eye to approximately 2 per cent of the operating range for any given condition. For the 4x5-degree beam this distance is about 100 yards for an observer in the center of the beam, and the filter used corresponds approximately to the Polaroid XR7X25 material. Less dense filters may be successfully used with the larger beam angles.

Optical Principles of Transmitter. The transmitter contains three mirrors: (1) an ellipsoidal mirror 4.5 inches in diameter; (2) a concave glass grid mirror 4.25 inches in diameter, coated with reflecting strips of aluminum or gold approximately 1/16 inch wide, alternated with clear spaces of exactly equal width; (3) an electrically vibrated concave mirror in the shape of an oval 9/16x3/4 inch, located at the focus of the grid mirror. Radiation from the lamp filament is reflected from the ellipsoidal mirror through the clear spaces of the grid mirror and is focused on the surface of the concave mirror. The concave mirror focuses an image of the grid back on the surface of the grid mirror. The diffuse image of the filament on the surface of the vibrating mirror acts as a source of variable intensity for the transmitter beam, which is projected by the grid mirror. The intensity of the transmitted beam is varied in the amount of radiation reflected from the grid mirror as the image of the grid is oscillated across the mirror surface by the motion of the vibrated concave mirror.

Other Infrared Optical Telephones. Incandescent tungsten lamps have been used as the radiation source in several German, Italian, and Japanese optical communication systems for voice and code, some of which have been analyzed in reports[7,8,9] submitted by the University of Michigan and Northwestern University. The more successful systems, though differing in detail, utilize some mechanical-optical principle for modulating the steady radiation from a direct-current-operated source. Systems in which the radiation is modulated by operating the source on voice-modulated current have apparently been a good deal less successful.

Some of these communication systems are briefly described, together with their operating characteristics in Chapter 4.

Microflux Source for a Photocell Test Set[10]

In order to permit standardization and easy intercomparison of test results obtained by various contracts of Section 16.4 and by the associated military laboratories in which related work was being carried out, a photocell test set was designed and constructed by the University of Michigan under Contract NDCrc–185. The equipment consisted of a microflux source together with especially designed electrical measuring equipment. In accordance with the system mentioned in Section 1.1.3, a tungsten lamp calibrated for operation at the color temperature of 2848 K is used as the source of radiation, attenuated in the microflux source to a known magnitude of the order of a few microhololumens, for testing the responsivity, frequency response characteristics, and noise holothreshold of near infrared radiation detectors.

A recording microphotometer type of lamp (for example, Mazda 1708 with C–6 filament, S–11 bulb, single-contact bayonet base, rated at 4.8 volts, 4.5 amperes) proved to be most convenient for this purpose. As mounted in the test set, the *holocandlepower* of this lamp is approximately 20 in a direction perpendicular to the filament when the lamp is operated at the color temperature of 2848 K. A number of other small tungsten lamps, for example, lamps of the photocell exciter type having a C–6 filament, are also suitable. Since at the mentioned color temperature most of these lamps are operated at 15 to 20 per cent below their rated voltage, their life is quite long. It is found that, after being properly seasoned, a lamp may be used for a period of 100 hours or more without being recalibrated, while an accuracy of ±5 per cent or better is maintained which is entirely satisfactory for ordinary test purposes. This equipment and its mode of use are more fully described in Chapter 3.

1.2.2 Recognition and Code Communication Sources

One of the more important applications of incandescent tungsten lamps is in the beacons which constitute a part of the type D recognition and code communication systems described more fully in Chapter 5. These systems were developed under a BuShips project. A closely related development for BuAer is briefly described at the end of this section.

The Type D Beacon

The first type D equipment[11] constructed and demonstrated to the Armed Services was intended for ship-to-plane recognition only, without provision for communication between two stations. A standard tungsten projection lamp (C–13 monoplane filament, T–20 bulb, 115 volts, 500 watts, medium prefocus base) was used as the source of radiation. The rated life for this lamp is 50 hours, and the approximate initial lumens, 13,000. Because of the large thermal inertia, this lamp could be operated satisfactorily from a standard 60-cycle line, since the receiver was so constructed that the small amount of 120-cycle modulation did not prevent satisfactory operation.

The lamp was surrounded by two coaxial cylindrical brass shutters to modulate and code the emitted radiation. The inner modulating cylinder contained nine segments of 20 degrees each, separated by clear segments of equal width. The outer cylinder was made in adjustable sections such that any code letter of three elements could be superimposed on the radiation already modulated by the inner cylinder. The repetition rate of the code recognition symbol was 40 times per minute. The tops as well as the sides of the cylinders were segmented and the base of each and the mounting for the beacon were considerably below the lamp filament so that the vertical zone of coverage extended from below the horizontal plane to about 10 degrees from the zenith. Azimuthal coverage of 360 degrees was provided at all angles of elevation within this vertical zone of irradiation.

The rotating cylinders were enclosed in a glass dome 5 inches in diameter and 9 inches high, the inner surface of which was covered with a layer of Polaroid infrared transmitting filter approximately equivalent to XR7X25. With this filter the visible range of the source for the dark-adapted naked eye was only a few feet, while the magnitude of the receiver response using a thallium sulfide cell detector (see Chapter 3) was reduced to about 30 per cent of its value with no filter. To prevent overheating of any portion of the beacon, the air inside the dome was circulated by means of a small blower.

In the construction of subsequent models,[12] emphasis was placed on providing for communication as well as recognition, primarily from ship to ship rather than from ship to plane. Means for communication were provided through a manually operated key which controlled the application of power to the lamp filaments. The lamp could also be operated from an automatic coder designed to transmit continuously the code letter or group of letters designated as the recognition symbol for the given period. The outer of the two rotating cylindrical shutters in the model described above was therefore dispensed with, since its function of coding the transmitted radiation was superseded in this manner, and the modulating shutter was redesigned.

At the request of NDRC a special tungsten lamp was developed by the Lamp Development Laboratory of the General Electric Company for use in this beacon. The new lamp was designed to permit higher keying speeds and more uniform intensity distribution in the plane perpendicular to the axis than were possible with the standard projection lamp used in the earlier model. A lamp of the type finally developed for Navy use is shown in Figure 1. It has a T–14 heat-resistant envelope and medium bipost base with a maximum overall length of 6⅜ inches. The 4C12 filament is rated at 110 volts, 500 watts, with an approximate life of 200 hours. Its mean horizontal candlepower, when mounted base down, is approximately 1,000.

The lamp is enclosed in a concentric cylindrical brass modulating shutter having three open and three closed segments, each 60 degrees in width. A synchronous motor drives the shutter at 30 rps, thereby modulating the emitted radiation at 90 cycles per second. Around the shutter is a small inner cylinder of clear glass, and around this is a cylindrical Fresnel marine lens. On the outer surface of the cylinder and the inner surface of the Fresnel lens is a sheet of Polaroid infrared transmitting filter selected so that the combined transmission by the two layers is approximately equivalent to that for XR7X25 material. Thus, if one layer of the filter material fails or is fractured, the visual security of the beacon is not impaired to the same extent as if there were only one layer. To insure 360-degree azimuthal coverage it was necessary to install two beacons on each ship to avoid obscuration of certain zones by the ship's own structure. The Fresnel lens concentrates from one to three times the intensity which would exist in its absence into a zone extending ±11 degrees from the horizontal, while at larger angles the intensity is correspondingly reduced. Use of the lens is therefore advantageous only for signaling near the horizontal plane, as from ship to ship, and is to be avoided when nearly

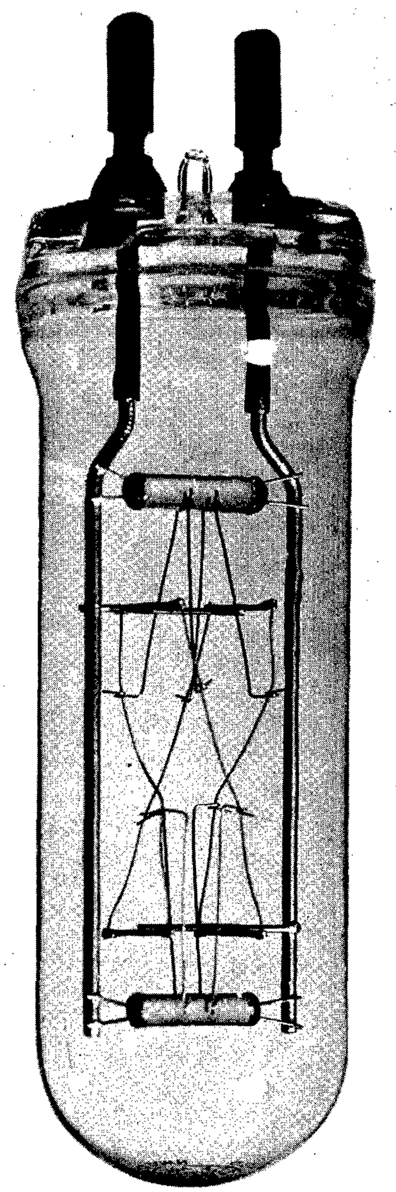


FIGURE 1. Incandescent tungsten lamp for the type D beacon.

hemispherical coverage is desired, as from ship to plane. In later models an infrared transmitting glass was used either for the plain inner cylinder or for the Fresnel lens. Forced air circulation and conducting fins were incorporated in the beacon to provide adequate heat dissipation during continuous use at high ambient temperatures.

With these transmitters and the associated receivers it is possible to transmit code at an estimated speed of 10 to 12 words per minute. One source of difficulty initially encountered in code reception arose from the fact that the lamp filament cooled more completely in the time interval between letters than in the interval between elements of a letter. For this reason "inrush keying" systems [13] were later developed by means of which a higher than normal voltage is applied to the filament at the beginning of each element. These methods, described more fully in Chapter 5, result in improved "crispness" of the transmitted code symbol elements.

Operational tests of this system indicated the desirability of devising means by which the receiving ship might break in at any time during the transmission of a message. With the beacons just described this is impossible, because although the signal flux emitted during the intervals between elements, letters, or words when the filament is cooling is small in comparison with the signal flux emitted when the filament has reached its equilibrium operating temperature, nevertheless the signal from the local source during these intervals is quite large in comparison with a signal from the receiving ship. The modulated radiation emitted from the local source during the cooling time of the filament therefore blocks out reception from a distant source and prevents break-in by the receiving operator. For this reason a radically different type of beacon was developed. It is described in the following section, while associated changes in receiver-amplifier design which were necessitated to secure the feature of two-way break-in operation are described in Chapter 5.

The Type D–2 Beacon [13]

The type D–2 beacon was developed to permit code transmission at a higher speed than was possible with the type D and to eliminate modulation of the local beacon during filament cooling time between code elements so that it would be possible for a distant operator to break in at any time during the transmission of a message. It is seen that the second objective might be achieved by direct electrical modulation of the source, since modulation would cease as soon as the lamp current was interrupted by releasing the transmitter key. However, in order to achieve a high modulation ratio (see Section 1.1.4) when it is desired to modulate the radiation from a tungsten lamp by direct operation from a modulated power supply, even at a low audio frequency such as 90 cycles per second, the thermal inertia of the filament must be reduced to the lowest practicable point through the use of extremely fine wire. For example, if it is assumed that the rate of cooling of the filament is proportional to the area of the incandescent surface, it follows that the ratio of the rate of cooling to the heat capacity of a cylindrical filament is inversely proportional to the radius of the filament, and that this ratio will continue to increase as the radius of the filament is reduced to the smallest practicable value. If an adequately high percentage modulation of radiation from an incandescent filament is to be achieved by direct electrical means at any given frequency, the filament must cool down during each cycle to a temperature such that the thermal radiation emitted at this temperature will be quite small compared with that emitted at the peak temperature, and this cooling must occur rapidly enough to require only a portion of the cycle. Conversely, such a filament will rise quite rapidly to its peak equilibrium temperature in the remaining portion of the cycle during which power is supplied. The incandescence time can sometimes be reduced by altering the waveform of the power supply to permit momentary overvoltage on the filament, thus increasing the portion of the cycle available for nigrescence.

Preliminary experiments indicated that commercially available lamps of the 6S6 and 10S6 types could be used successfully as current-modulated radiation sources at frequencies up to 90 cycles per second. The lamp finally used for this purpose is the 10S6 type (230 volts, 10 watts, C–17 filament, S–6 bulb, intermediate screw base). A lumen output rating for this particular lamp is not available, but a comparison with values for similar lamps indicates that it should be about 60 to 65 lumens. The rated life is 1,500 hours. The mode of operation used in the electrically modulated type D–2 beacon may affect the service life of the lamp to some ex-

tent, although preliminary tests indicated that any such effect is not large.

A thyratron-controlled power supply was especially designed and constructed to operate these beacons. Under manual or automatic key control, power from the three-phase, 60-cycle ship supply is converted to current pulses for operating the 10S6 lamps at a frequency of 90 cycles per second. By means of controls provided in the power supply, the shape and the duration of the current pulses can be adjusted to provide a maximum percentage modulation of the emitted radiation. The power input to the beacons may also be varied as desired. It has been found that satisfactory operating characteristics are retained, including reasonably long lamp life, when the power input to the lamps is up to thirteen per cent greater than their normal power rating for use on direct current or symmetrical alternating current.

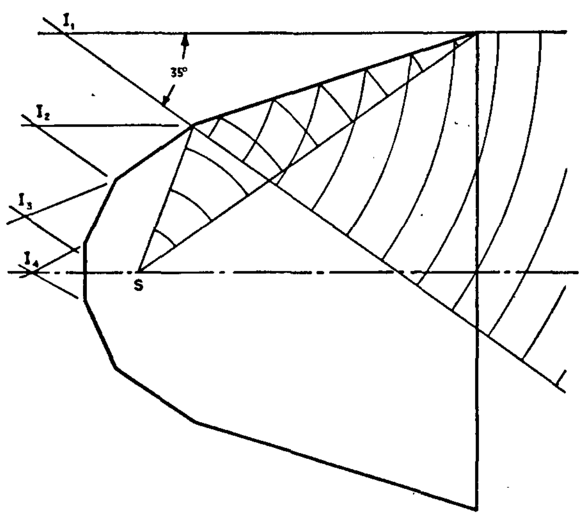


FIGURE 2. Contour of reflector for the type D–2 beacon.

A type D–2 beacon unit contains fifteen lamps mounted in a row along a specially designed reflector having the cross section shown in Figure 2. The reflector, which has an Alzak surface, is made of sheet metal bent to form seven plane reflecting surfaces so oriented as to give a nearly uniform beam intensity distribution within the zone comprising 30 degrees above and below the lengthwise plane of symmetry of the reflector. Thus a ship on which the beacon is installed may roll through any angle up to 30 degrees from the vertical without appreciably affecting the intensity of the signal transmitted to the receiving station. The details of construction for one beacon unit are shown in Figure 7 of Chapter 5. Eight beacon units, mounted with the long dimension horizontal and oriented in octagon array, provide uniform azimuthal coverage over the entire horizon.

Each beacon is covered with an appropriate infrared transmitting filter. The filter having the most efficient optical properties for this purpose is either a Polaroid polyvinyl alcohol film, code XRN5PX65, sandwiched between two clear glass plates, or Ohio State University filter material, code DR23u, coated on one side of a clear glass plate. Either of these filters provides a visual security distance of about 500 feet and reduces the response of the receiver about 48 per cent. The best all-glass filter is Corning 2568, 8 ± 0.5 millimeters thick. Such a filter provides a visual security distance between 400 and 1,200 feet and reduces the signal response of the receiver about 69 per cent. The general characteristics of these various types of filters are discussed in Chapter 2.

An octagon array of these beacons contains 120 lamps and has a normal power rating of 1,200 watts. The signal intensity from such an array operated at 1,200 watts from the type D–2 source power supply was found by test to be about 12 per cent greater than that of a type D beacon containing a single 500-watt lamp designed for it, when both beacons were covered with approximately 8 mm of Corning 2568 infrared transmitting filter glass. However, the type D–2 beacon, being an extended source, can be covered with a less dense filter than the type D beacon while the same visual security range is maintained. This possibility, if combined with operation of a type D–2 beacon at a 13 per cent power overload, results in a ratio of modulated radiant signal intensity to electrical power input about 70 per cent as large as for the mechanically modulated type D beacon. The type D–2 not only has no mechanical moving parts but also makes possible the break-in feature of operation between two stations, since as soon as the key is released at the transmitting station there is no modulated local signal radiation to interfere with reception of the much weaker signal from the distant station. The operator of the distant station may break in at any time merely by depressing and holding down his key. The local operator at once observes that his

monitor signal lamp is no longer following his own signal transmission and interrupts his transmission to await the message which the distant operator wishes to interpolate. The features of receiver design which were necessary to achieve this break-in feature in the operation of a complete system are described in Chapter 5.

In field tests of the complete type D–2 system made at the Bureau of Ships test station, Fort Miles, Cape Henlopen, Delaware, in March 1945, a signaling speed of 30 words per minute was established, the speed being limited by the skill of the operator rather than by limitations of the equipment. Satisfactory operation of the break-in feature was also demonstrated. Additional laboratory tests were made using an automatic keying device to code the type D–2 sources and a recorder system to register the output of the type D–2 receiver. The recorded signals were readable up to a code speed of 40 words per minute, which was the maximum speed obtainable with the keying device. In view of the excellent results achieved with the type D–2, BuShips negotiated direct contracts for the quantity production of the beacons and other components of this system.

Source for Plane-to-Plane Recognition System [14]

The development of a modulated, coded, infrared plane-to-plane recognition system was carried through the stage of laboratory tests on preliminary equipment by the University of Michigan under Contract NDCrc–185. The lamp used as the source in this equipment is similar to the 10S6 lamp used in the type D–2 beacon, differing only in its voltage and power ratings, and is operated in a manner closely analogous to that utilized for the type D–2 beacon.

Each source consists of one 6-watt, 115-volt, type 6S6 incandescent lamp mounted without a reflector in a small aircraft wing nacelle of the type used for navigation lights. The nacelle cover is coated with a layer of either Polaroid or the Ohio State University infrared transmitting filter having an optical density such that the visible range of the lamp is less than 100 feet. Complete spherical coverage is provided by mounting one source above and one below each wing tip. The sources are operated from the 800-cycle power supply of Navy aircraft and modulated by interrupting the current to the lamp 90 times per second by means of a motor-driven commutator. An automatic coder which controls the application of power to the lamps makes it possible to transmit any one of some four hundred different two-letter code combinations. When operated in this manner with a power input of six watts, each source is equivalent to a bare 4-candlepower tungsten lamp modulated by a rotating disk having equal opaque and transparent sectors. A 30 per cent increase in signal intensity may be achieved by a 13 per cent increase in the power supplied to each lamp. Although the life of the lamp would be somewhat reduced by such an overload, it would still be adequately long for this application.

The complete recognition system of which this source constitutes one component is described in Chapter 5.

1.3 GASEOUS DISCHARGE LAMPS

1.3.1 Flash Lamps

Early Designs

All the flash lamps described in this chapter were developed primarily by the University of Michigan under Contract NDCrc–185. They were first investigated as possible sources of near infrared radiation in apparatus for the detection of night-bombing planes.[15] Experimental lamps were constructed in a variety of shapes and sizes. Some were air-cooled, some were water-cooled; some had mercury electrodes, some had tungsten or other solid metal electrodes; some had straight capillary discharge tubes, in some the discharge occurred through one or two helical spiral coils. However, the best infrared radiation characteristics were invariably obtained when the lamps were filled with one or more of the rare gases, especially argon, krypton, or xenon. In air-cooled lamps, regardless of whether the outer envelope of the lamp was of glass or quartz, it was necessary to provide ballast volume to permit non-explosive expansion of the gases suddenly heated in the high-energy discharge region of the lamp. Despite rather stringent limitations on flashing rate and energy input per flash, these early lamps showed sufficient promise as sources of near infrared radiation to warrant their future specialized development for other specific applications later requested by the Armed Services. However, the military requirements for these applications restricted the later developments to lamps of the air-cooled type.

THE TYPE 10 HIGH-INTENSITY FLASH LAMP [16,17]

The type 10 high-intensity flash lamp was developed in response to an informal request by the Army Air Corps for a source suitable for illuminating the target area in connection with guided-missile bombing. The principal requirements outlined in the request were: (1) the peak instantaneous flux emitted in the near infrared should be as large as possible; (2) the lamp should not require forced cooling; (3) the firing circuit and associated equipment should be kept as light and compact as possible; (4) the operating potentials should be kept as low as possible to avoid spark-over trouble under high-altitude conditions; (5) the dimensions of the lamp should be kept small in order that it might provide a narrow beam of high intensity when used in conjunction with a suitable reflector.

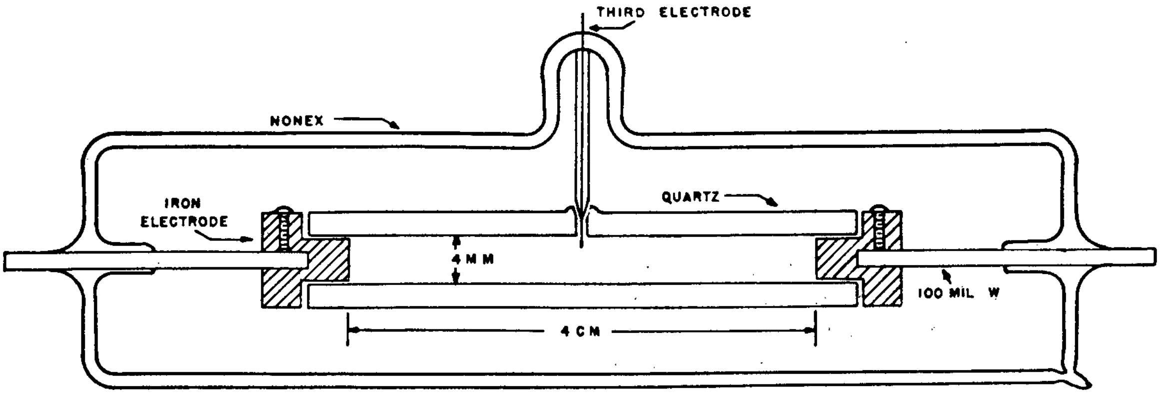


FIGURE 3. The type 10 high-intensity flash lamp.

Design of the Lamp. The design of the type 10 flash lamp is shown in Figure 3. The discharge is confined to a length of 4 centimeters within a quartz capillary tube of 4 millimeters inside diameter and 2 millimeters wall thickness. The main electrodes are of iron, turned to fit snugly into the ends of the quartz tube and supported on 100-mil tungsten leads. The life of the lamp is materially lengthened if the electrodes are tipped with alloy electrode pellets of low work function obtained from the firm of Edgerton, Germeshausen and Grier, Cambridge, Massachusetts. The outer envelope, made of Nonex glass, is approximately 8 centimeters long and 2 centimeters in outside diameter. The third electrode consists of a 30-mil tungsten wire sealed into the envelope with one end extending into a small hole blown in the center of the quartz discharge tube to provide a means for external triggering control. After being outgassed, the lamp is filled with a mixture consisting of 90 per cent krypton and 10 per cent xenon to a total pressure of 20 to 70 centimeters of mercury. The intensity of the flash is almost independent of pressure within this range, and since the lamp is triggered by means of a third electrode the voltage to which the firing condensers must be charged is also unaffected by the gas pressure.

Method of Firing. The normal method of firing this lamp utilizes a Tesla coil to pass a high-voltage spark from the third electrode to one or both of the principal electrodes. A 25-μf condenser connected across the lamp terminals then discharges through the conducting gas, producing the high-intensity flash. The condenser is charged to a potential of 1,000 to 2,000 volts from a suitable power supply with a protecting resistor in series. The rate of flashing may be manually controlled, or the lamp may be fired automatically at a rate up to three flashes per second by means of a motor-driven cam and switch arrangement used to energize the primary of the Tesla coil.

Radiation Characteristics. Both the duration and the peak intensity of the flash are affected by the constants of the electric circuit which is used to fire the lamp. The values given in Table 1 were obtained with the lamp connected by short leads to a 25-μf condenser.

The intensity versus time characteristics of the flash have been investigated by a photographic method utilizing a rotating mirror arrangement and by a special oscillograph utilizing a cesium-surface vacuum phototube as the detector. The peak intensity is attained 6 to 8 μsec after the beginning of

the flash, while the total elapsed time from the beginning of the flash until the intensity has decayed to about 15 per cent of the peak value is 30 to 35 μsec.

The peak hololuminous intensity versus energy input per flash in a direction perpendicular to the axis of the lamp, measured with reference to the cesium-surface vacuum phototube, is shown in Table 1. Up to an input energy of about 20 joules

TABLE 1. Energy input per flash and peak intensity of the type 10 lamp relative to a cesium-surface vacuum phototube.

Firing potential (volts)	Energy input from 25-μf condenser (joules)	Peak intensity (equivalent holocandles)
1185	17.6	1.0×10^9
1300	21.1	1.2×10^9
1815	41.2	2.2×10^9
2060	53.1	2.7×10^9

per flash the lamp may be fired continuously at the rate of three flashes per second without excessive overheating. Above 20 joules per flash a lower rate of firing is recommended. If the power input becomes too high the quartz discharge tube becomes so hot that the triggering circuit no longer controls the rate of firing, and the life of the lamp is shortened. For applications in which larger dimensions could be tolerated, the permissible power input might be correspondingly increased without the necessity for adding forced cooling methods.

The beam holocandlepower at the peak of the flash and the angular distribution of intensity in the beam have been measured with the type 10 lamp mounted lengthwise on the axis of a glass second-surface precision parabolic reflector of 19⁷⁄₁₆-inch aperture and 7⅞-inch focal length. These measurements were made for five different positions of the lamp along the axis of the reflector, and the results are shown in Figure 4. For curve 1, three sets of experimental points are shown. These represent the angular distribution of intensity obtained with the center of the lamp at the focal point, and at a distance of 1 centimeter from the focal point along the axis both toward and away from the reflector. The distribution is so nearly identical for these three positions of the lamp that only one curve has been drawn for the three separate sets of points. For curves 2 and 3, the two extremities of the discharge were located in turn at the focal point of the reflector; for curve 2 the lamp extended toward the reflector from the focal point, while for curve 3 the lamp extended away from the reflector beyond the focal point. The peak axial beam holocandlepower of about 1.6 billion shown in the figure is for an energy input of 41.2 joules per flash, with the lamp operated under the same conditions and using the same detector as for the corresponding entry shown in Table 1 for the bare lamp without reflector.

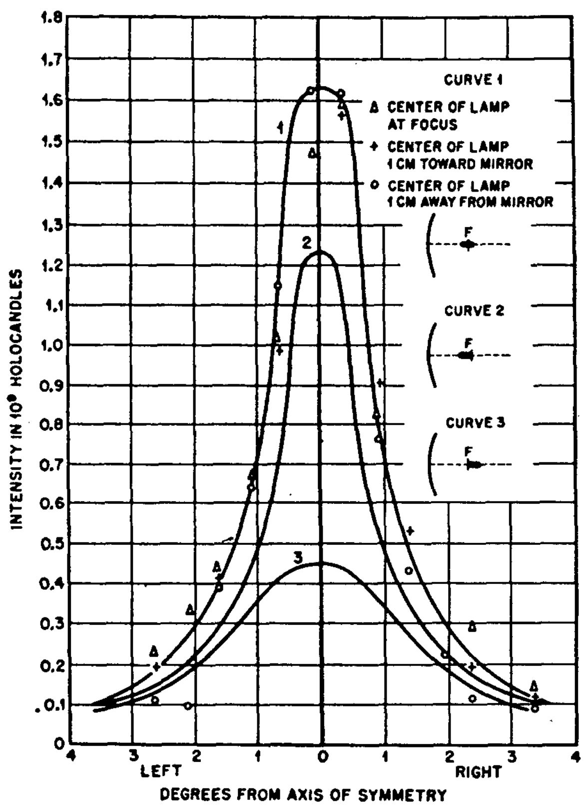


FIGURE 4. Intensity distribution across the beam projected from a type 10 lamp mounted in a 19⁷⁄₁₆-inch reflector of 7⅞-inch focal length, with reference to a cesium-surface detector.

Life tests have been made with the lamp flashed three times per second at an input energy of 21 joules per flash. For a bare lamp with iron electrodes, the peak flash intensity is reduced to 75 per cent of the initial value after about 3,000 flashes, or 15 to 20 minutes of continuous operation. For a bare lamp with the special alloy electrode pellets referred to above, the corresponding figures are 22,000 flashes, or about two hours of continuous operation. Under these same firing conditions, the

infrared component of the radiation decays much less rapidly with time than the peak intensity of the total lamp radiation to which the phototube responds. For example, when the lamp is covered with a Polaroid XR3X44 filter, the lamp may be flashed about 8,000 times, corresponding to about 45 minutes of continuous operation, before the peak intensity of the transmitted component of the radiation is reduced to 75 per cent of its initial value.

Table 2 shows the ehT values (see Appendix) of certain infrared transmitting filters for the radiation from a new type 10 flash lamp, with respect to a cesium-surface vacuum phototube. The plastic membrane filters were supported between two clear glass lantern slide plates for the absorption and reflection of which no correction has been made. For comparison, the standard values (ehT°) for the same filter samples with respect to radiation of standard distribution from a 2848 K tungsten source are also given. Somewhat higher ehT values than those listed are obtained when the lamp is operated at a lower energy input per flash. Moreover, because of the slower rate of decrease for the infrared component of the radiation mentioned in the preceding paragraph, the ehT values tend to increase during continued use of the lamp.

TABLE 2. Effective holotransmission of certain filters with reference to a cesium-surface detector.

Filter	ehT for radiation from type 10 lamp	ehT° for radiation from 2848 K tungsten source
Wratten 87	0.11	0.38
Polaroid XR3X44	0.043	0.19
Polaroid XR7X30	0.025	0.13
Corning 2600 5.0 mm	0.15	0.36
Corning 2550 2.0 mm	0.073	0.27
Corning 2540 2.6 mm	0.024	0.13

A small quantity of lamps based on the Michigan type 10 design was constructed by the Westinghouse Electric Corporation for the Army Air Forces. It is believed that facilities for large-scale commercial production could readily be set up if desired, and that the fundamental design features of the lamp could be easily adapted to other shapes and sizes which might be required for specific applications of a source of this type.

THE TYPE 200 MICROFLASH LAMP [18,19]

The type 200 microflash lamp and an associated firing unit for use in ballistic photography were developed at the request of Aberdeen Proving Ground as Project Control OD–147. In order to "stop" completely a high-speed projectile it is essential that the duration of the flash be no more than a few microseconds; it is also essential that the lamp be triggered through an arrangement which permits synchronization of the flash with the shell trajectory and that an area sufficiently large to "catch" in flight projectiles up to 12 or 16 inches in diameter be illuminated at a sufficiently high intensity to register on the film. These requirements have been successfully met with the equipment described below.

Although the type 200 lamp has been used primarily as a source of visible radiation for ballistic photography, it is in part an outgrowth of the type 10 lamp described above and, in turn, contributed to the development of the type 300 microflash lamp described in a subsequent section.

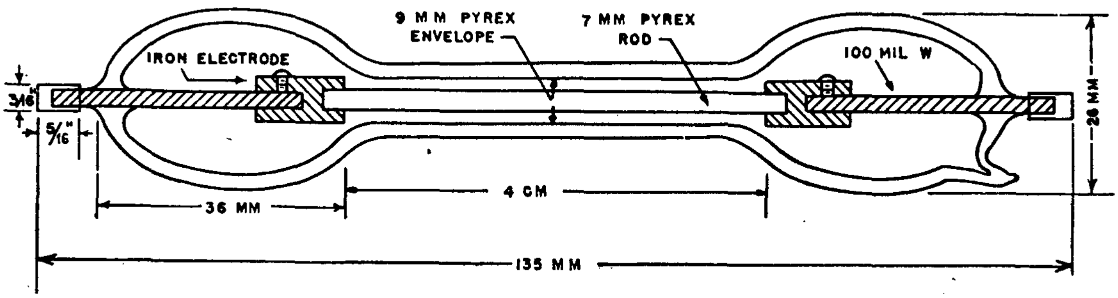


FIGURE 5. The type 200 microflash lamp.

Design of the Lamp. The general design of the lamp, together with the recommended dimensions, is shown in Figure 5. The discharge is confined to the annular space between the Pyrex rod and the concentric cylindrical Pyrex glass envelope which surrounds it. The short duration of the flash appar-

ently results from recombination of ions at the solid surfaces which are everywhere closely adjacent to the discharge. By providing ballast volume to permit expansion of the gas heated by the discharge, the bulbs at the ends of the lamp tend to quench the oscillations which may occur in the discharge and in the resulting radiation and also help to lengthen the life of the lamp.

If the energy input to the lamp is to be high (of the order of 25 joules per flash), it is important that the wall thickness of the Pyrex tube from which the outer envelope is made be at least 2 millimeters. Lamps constructed of quartz would have much greater mechanical strength, but the Pyrex construction is much simpler and ordinarily provides adequately long life. The life of a lamp depends critically upon the conditions of use and may be as short as twenty flashes at 25 joules per flash. Careful annealing of the tungsten seals is also an important factor in lamp life.

The lamp is filled with a gas mixture consisting initially of 90 per cent krypton and 10 per cent xenon, enough hydrogen being added to enable the lamp to withstand a given firing condenser voltage until it is triggered. To withstand 11,000 volts, for example, enough hydrogen must be included to contribute about 25 per cent of the total pressure of 45 to 55 centimeters of mercury to which the lamp is filled. The hydrogen also helps to suppress oscillations in the discharge. An external loop or band of wire around the middle of the lamp serves as a satisfactory triggering electrode for use with a spark coil or a Tesla coil.

Method of Firing. Since a flash of short duration can be obtained only if the time constant of the associated electric circuit is kept small, it is necessary to fire the lamp from a condenser of relatively low capacitance and to achieve a high energy input per flash through the use of a correspondingly high voltage. In the microflash unit, therefore, the lamp is fired from a 0.5-μf condenser, consisting of two 1.0-μf condensers in series, charged to a maximum potential difference of about 11,000 volts. The condenser is charged by a suitable voltage-doubler power supply. To trigger the lamp at the proper time for photographing a projectile the output from a suitably located microphone, photocell, or electrostatic loop is amplified and applied to the grid of a thyratron tube, which then discharges a condenser through the primary of a spark coil. The resulting electric pulse in the secondary of the coil, which is connected to the triggering loop around the lamp, initiates the flash.

The life of the lamp will be extended by operation at the lowest voltage which will provide a flash of the required intensity. The lamp is designed only for intermittent use, as in ballistic photography, and will not withstand successfully a high rate of firing at the large energy input per flash needed to produce the required radiant intensity.

The complete microflash unit, consisting of a type 200 lamp, a 12-inch parabolic reflector with Alzak diffusing surface, the trigger circuit, the lamp firing circuit, and a power supply unit designed to operate from a standard 115-volt, 60-cycle power line, is compactly mounted in a portable case approximately 10x13x17 inches.

Radiation Characteristics. The duration of the flash has been measured by two independent methods. When the rapidly moving image projected from a rotating mirror is recorded on orthochromatic film, a photographic duration time of 1 to 2 μsec is obtained. When the duration is measured with a cesium-surface vacuum phototube and a special oscillograph having a high-speed calibrated sweep, a value of 4 to 5 μsec is observed from the beginning of the flash until the intensity has fallen to about 15 per cent of the peak value. The difference in the results of the two methods is attributed to the tendency of the photographic film to respond only to the highest intensity portion of the flash, thereby failing to record an undetermined portion of the total duration.

When the lamp is fired from a 0.5-μf condenser charged to 10,000 volts (25 joules input per flash) the peak intensity of the flash is about 5×10^6 equivalent holocandles with respect to a cesium-surface detector; the peak hololuminous intensity value would probably be considerably higher for a detector having the spectral response characteristic of orthochromatic film. The ehT values for near infrared filters with reference to the type 200 radiation and a cesium-surface detector are only about one-half as large as the values shown in Table 2 for radiation from the type 10 lamp. It is possible that the discrepancy in flash duration measurements by the two methods outlined above may be partly due to differences in the duration characteristics of the high-intensity visible component of the radiation to which the orthochromatic film responds, and the

near infrared radiation of much lower intensity to which the cesium-surface phototube principally responds.

In use the lamp is mounted coaxially along the axis of a 12-inch diffusing surface parabolic reflector of 2.5-inch focal length with the center of the lamp approximately at the focal point of the reflector. The illumination provided by this arrangement is sufficient for ballistic photography over the entire field (30 to 40 degrees) of a camera placed near the microflash unit.

Performance. After their superior performance characteristics had been established in preliminary trials, four complete microflash units and an additional supply of type 200 microflash lamps were delivered to the Ballistic Research Laboratory, Aberdeen Proving Ground, in accordance with the request made in Project Control OD–147. The performance of both lamps and microflash units has apparently been satisfactory in every respect. A sample photograph of a 6-inch shell in flight at approximately 2,800 feet per second is shown in Figure 6. Chalk was rubbed on the shell to improve its contrast with the background. The photograph was taken by reflected light at a distance of about 150 feet from the muzzle of the gun. It is seen that both the translational and the rotational motions of the shell were completely stopped. The microphone used to trigger the flash from the bow wave of the shell is seen at the lower right.

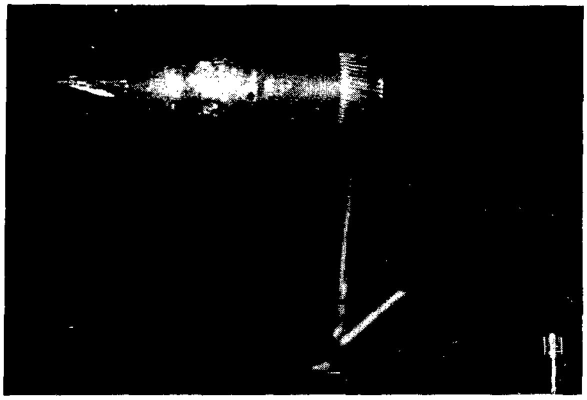


FIGURE 6. Six-inch projectile photographed with the type 200 microflash unit.

As a result of the superior performance of the microflash unit, the Army Ordnance Department has completed preliminary negotiations for the commercial production of a supply of type 200 lamps, and possibly also for the production of a number of additional complete microflash firing units.

Related Developments. Two related developments have been made by the University of Michigan for use in ballistic photography. One is a device [20] to trip a camera shutter automatically at just the proper moment to catch a projectile in flight when it is illuminated by the microflash unit. This device permits ballistic photographs to be made during the day or on a lighted range at night. This development was made on the basis of an informal request by the Army Ordnance Department during the course of the work on the microflash unit under the project previously mentioned. The second development [21] was made as Project Control OD–173. It consists of an adaptation of the type 10 lamp to illuminate a clock face at just the proper moment so that its image will be registered on each frame of a DeBrie high-speed movie camera used by the Aberdeen Proving Ground.

THE TYPE 300 MICROFLASH LAMP [22]

The type 300 microflash lamp was produced at the Lamp Development Laboratory of the General Electric Company with the consultation and assistance of the University of Michigan flash lamp group, to serve as a pulsed radiation source in equipment for detecting the range and direction of certain types of targets by means of near infrared radiation (see Chapter 6). It was initially desired that the source be capable of continuous operation at the rate of 60 to 120 flashes per second for periods of several minutes at a time, that its integrated useful life be at least several hours, that the amplitude of successive radiation pulses be essentially constant, and that each pulse have a duration of only about 1 μsec and the highest possible peak intensity in the near infrared. The type 300 lamp successfully meets all these requirements and has been used in models of the equipments for which its development was undertaken.

Two preliminary lamp designs,[22a] designated types 240 and 250, were developed by the University of Michigan. In each of these designs, as in the type 10 and in the type 200 lamp designs, the arc discharge is adjacent to a solid quartz surface. Although the radiation characteristics of these lamps are quite similar to those described below for the type 300 lamps, both designs were discarded because

the useful life of these lamps was too short for satisfactory service in the intended application.

The designation "type 300 microflash lamp" has been used only by NDRC. The General Electric Company has so far designated the lamp simply a "short-gap double-ended lamp." In this chapter, however, no distinction will be made between the lamps constructed by the General Electric Company and those constructed by the University of Michigan Contract NDCrc-185. Most of the variations in lamp design for the purpose of investigating the effect of various factors on the properties of the lamps, as well as the experimental investigation of these properties, were carried out by the University of Michigan group.

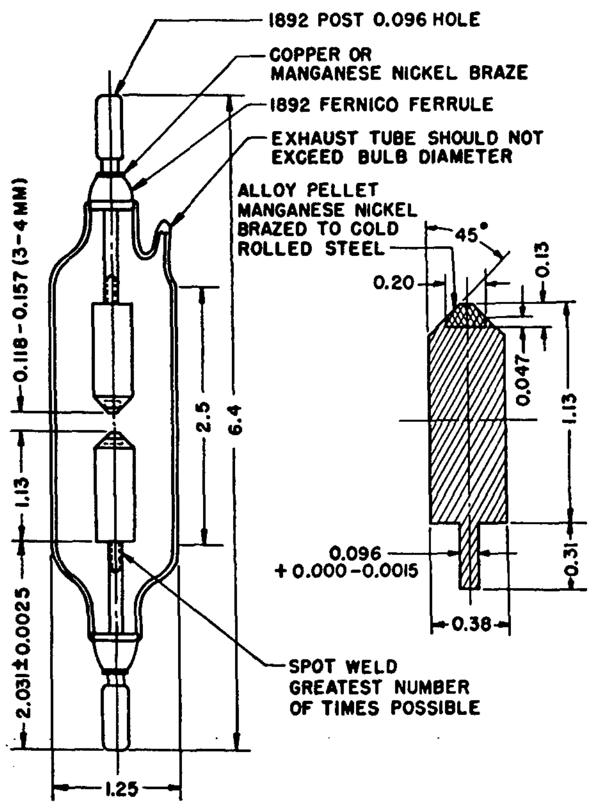


FIGURE 7. The type 300 microflash lamp.

Design of the Lamp. The design of the type 300 lamp and the standard dimensions used by the General Electric Company are shown in Figure 7. The design is simple and lends itself readily to large-scale production techniques. An important feature in securing long operating life is the use of the low work function alloy pellets, mentioned above in connection with the type 10 lamp, with which each electrode is tipped. After the lamp has been evacuated and outgassed it is filled with one or more of the rare gases, plus 1 to 3 centimeters of hydrogen to increase the self-breakdown potential at which the lamp will fire. The total pressure may vary from 50 to 70 centimeters of mercury. Argon is the filling gas principally used by the General Electric Company.

In the lamps constructed at the University of Michigan the main steel electrodes are supported on 100-mil tungsten leads sealed into a Nonex or Pyrex envelope, with brass electrode caps brazed to the outer ends of the tungsten seals. In order to increase the intensity of the flash by increasing the firing voltage of the lamp are gaps up to 10 mm long have been used in some lamps as compared with the 3-mm gap of the standard General Electric design. With the longer gaps, it was found to be advantageous to decrease the diameter of the steel electrodes from 3/8 inch to 5/16 inch and to round off the sharp corners of the bevels at the tip of each electrode. Argon, krypton, and xenon were used as filling gases, both singly and in mixtures. A mixture of argon and krypton in approximately equal volumes was found to produce the most desirable over-all characteristics. However, the advantage of this mixture over pure argon is probably too small to make its use economically justifiable.

Method of Firing. In use, the lamp is connected directly across the terminals of a 0.1-μf condenser (a resistance of 0.5 ohm or less may be in series). The condenser is charged through a suitable protective resistor from a half-wave or full-wave unfiltered power supply, and the lamp is fired when the voltage across the condenser builds up to the breakdown potential of the lamp. It has been found advantageous to mount the lamp directly on one terminal of the condenser inside a coaxial cylindrical shield of brass or copper connected to the outer end of the lamp so as to serve as the second lead from the condenser. This arrangement provides good electric and magnetic shielding from the large peak discharge current (of the order of 2,000 to 4,000 amperes) and also provides a good means for dissipating the heat generated in the lamp. If the power supply is operated from a 60-cycle line, the lamp can be fired either 60 or 120 times per second without an auxiliary triggering system. The voltage at

which the lamp fires is determined by the details of its construction and the characteristics of the filling gas. Most lamps have been made to fire at voltages between 3,000 and 4,000 volts. The firing of the lamp may be controlled by means of a Variac in the primary circuit of the power transformer. By adjusting the voltage applied and the constants of the lamp-firing circuit so that the condenser is not charged to the full breakdown voltage of the lamp on each half cycle, it is possible to fire the lamp at integral submultiples of 60 times per second. Type 300 lamps have been operated continuously at 120 flashes per second for many hours. The flash repetition rate could probably not be increased much beyond this value without necessitating means for forced cooling of the lamp, which has hitherto been considered undesirable. As a consequence, this rate of flashing sets an upper limit to the feasible scanning rate for systems in which the lamp is used.

Radiation Characteristics. The arc discharge which occurs in the type 300 lamp consists of a thin central core of very high brightness surrounded by a sheath of lower brightness about 3 mm in diameter. Tests conducted by Western Electric Company (Bell Telephone Laboratories) Contract OEMsr-1267 indicate that the brightness of the central core is 10 to 20 times greater than that of the surrounding diffuse sheath and that the ehT values of infrared filters for radiation from the core are three or more times the values found for the radiation from the entire arc. The data given in Tables 3 and 4 refer to average values for the radiation from the entire arc in a number of representative lamps.

The data on lamp characteristics were obtained at the University of Michigan with a cesium-surface vacuum phototube coupled through a wide-band amplifier to the vertical deflection plates of a cathode-ray tube. This receiver was calibrated by using the radiation from a standardized tungsten lamp chopped by means of a high-speed slotted disk. The high-speed horizontal sweep of the cathode-ray tube was triggered by means of the lamp discharge current, so that a stationary pattern of the intensity versus time characteristics of the lamp radiation was presented on the screen of the cathode-ray tube. The lamps were fired 60 times per second from a 0.1-μf condenser. For a lamp which breaks down at 4,000 volts, this corresponds to an energy input of 0.8 joule per flash or a power dissipation of 48 watts in the lamp. The peak intensity of the first few flashes may be 20 per cent higher than the equilibrium values measured after the first few seconds of operation. Some typical average characteristics are summarized in Table 3. The duration

TABLE 3. Average radiation characteristics of representative type 300 microflash lamps. Capacitance of firing condenser, 0.1 μf. Firing potential, 3,000 to 4,000 volts for 3- to 4-mm arc length, 4,000 to 8,000 volts for 7- to 10-mm arc length (depending on arc length and on pressure and composition of the filling gas).

Arc length (mm)	Duration from beginning of flash down to 15 per cent of peak intensity (μsec)	Peak intensity relative to a cesium-surface detector (equivalent holocandles)	
		Bare lamp	Lamp mounted in 19½-in. precision parabolic reflector
3–4	1.6–2.4	$(0.7–2) \times 10^5$	$(2–4.5) \times 10^8$
7–10	1.7–2.7	$(1.8–5) \times 10^5$	$(1–2.5) \times 10^9$

of the flash between the points of half peak intensity is between 0.5 and 0.75 μsec for most lamps, the much longer duration values down to 15 per cent of the peak intensity, shown in the second column of the table, being due principally to the gradual decay of intensity at the "tail" of the curve. The beam candlepower values given in the last column of the table were obtained with the arc transverse to the axis and centered at the focal point of a second-surface precision glass parabolic reflector of 7⅞-inch focal length and 19⁷⁄₁₆-inch aperture. With a lamp having a 1-centimeter arc the angular dimensions of the beam projected from this reflector are approximately 1x3 degrees. Since the bright central core may be displaced by an amount greater than its own width through the effects of thermal convection currents, electrode surface irregularities, etc., successive flashes do not follow the same path with enough exactness to permit good measurements to be obtained for the intensity distribution across the beam.

The spectral intensity distribution of the radiation from these lamps has not been measured. However, as in the case of other flash lamps, it undoubtedly consists of the characteristic line spectrum of the filling gas superposed upon a continuous spectrum. The average ehT values of certain filters for radiation from the type 300 lamps with reference

to a vacuum cesium-surface detector are given in Table 4. These values are relatively independent of which of the gases indicated above is selected for filling the lamp. The highest ehT values for radiation from the entire arc were obtained with argon-filled lamps, while the highest values for radiation from only the central bright core of the arc were obtained with xenon-filled lamps. No correction has been made for the reflection and absorption of the two lantern-slide mounting plates between which the plastic membrane filters listed in Table 4 were supported.

TABLE 4. Effective holotransmission of certain filters with reference to a cesium-surface detector.

Filter	Average ehT for radiation from type 300 flash lamp	ehT° for radiation from 2848 K tungsten source
Wratten 87	0.074	0.38
Polaroid XR3X44	0.029	0.19
Polaroid XR7X30	0.017	0.13
Corning 2600 5.0 mm	0.085	0.36
Corning 2550 2.0 mm	0.047	0.27
Corning 2540 2.6 mm	0.017	0.13

Lamp Life and Performance. No type 300 lamp is known to have been operated either to destruction or to the end of its useful life as a radiation source. In a life test conducted by the Western Electric Company Contract OEMsr–1267, a General Electric lamp was fired 120 times per second from a 0.1-μf condenser with a 0.2-ohm resistor in series for a total of 450 hours in continuous periods of about eight hours each. This corresponds to nearly 200,000,000 flashes. After 210 hours the peak intensity of the flash had decreased to about 70 per cent of the initial value, due partly to a decrease of the lamp firing potential and partly to clouding of the glass envelope by material sputtered from the electrodes.

In view of the long life of these lamps it might be supposed that pulses of higher peak intensity could be obtained by operating the lamp from a larger condenser or at higher firing voltages. However, the duration of the flash increases much more rapidly than its peak intensity when the capacitance of the firing condenser is increased, and the radiation characteristics of the lamp become less desirable if the construction and processing are altered so as to increase the self-breakdown firing voltage appreciably above the range of values shown in Table 3. Some increase in peak intensity might be obtained if a control tube which would withstand higher voltages (such as an ignitron) were added to the firing circuit. With the addition of such equipment it might also be possible to fire the lamps at considerably higher rates than 120 times per second. However, the problems associated with supplying adequate electric power and adequate means for dissipating the heat developed in the lamp during continuous operation at high intensity will undoubtedly continue to limit the rate of flashing which is feasible.

The operation of these lamps in the equipment (see Chapter 6) for which they were developed has been very satisfactory. It is not known whether the General Electric Company plans to produce such lamps on a commercial basis but they will presumably continue to be available from this company on special order if not otherwise.

1.3.2 Concentrated-Arc Lamps

The concentrated-arc lamp [23] is a new type of radiation source developed by the Western Union Telegraph Company. In May 1943, when its development was still in the laboratory stage, Contract OEMsr–984 was negotiated with the Western Union Company for the further development and study of this type of lamp as an electrically modulated source of near infrared radiation for communication purposes, primarily in connection with Project Control NS–159.

During the contract period from May 1943 to August 1945 the basic theory of operation of the lamp was investigated, the design and methods of fabrication were improved, the number of useful sizes, types of construction, and operating circuits was increased, the desired radiation characteristics were enhanced, and the average operating life of the lamps was lengthened. Nearly 6,000 lamps of various types were supplied to the Armed Services and to other government agencies and contractors for wartime use. The principal application of the lamps by NDRC Section 16.4 was their use in the early models of an infrared voice and code communication system [24] (Navy type E) by Northwestern University Contract OEMsr–990. The active co-operation of those working under this contract in measuring the radiation characteristics and investi-

gating the basic mode of operation of the lamps was of material assistance in motivating and accelerating the successful improvements in design and construction of the lamps under the Western Union contract. Concentrated-arc lamps were also used by the Army in a narrow-beam, battery-operated aural signal unit for code and voice communication; by the Navy in a hand-held equipment of medium beam width for voice communication between airplanes, or between airplanes and ground stations; by various Armed Service agencies and contractors in boresighting equipment; and by the Office of Strategic Services in equipment for projecting aerial photographs from the same angle at which the exposures were made.

The Western Union Telegraph Company has also developed manufacturing facilities for lamps of several standard types which are now commercially available.[25] These standard types are rated at 2, 10, 25, and 100 watts. Except where otherwise indicated, the material which follows refers exclusively to lamps of these standard types.

Lamp Design and Construction

The name of the concentrated-arc lamp is derived from the small cathode spot of high brilliance from which, in the standard types of this lamp, the major portion of the radiation is emitted. These lamps consist basically of two permanent electrodes sealed into a glass bulb filled with argon gas at a pressure of one atmosphere. The unique radiation characteristics are largely due to a specially prepared zirconium oxide cathode. The major portion of the emitted radiation is a continuum having a spectral distribution similar to that of a black body near 2800 K. Superimposed on the continuum are intense spectral lines which originate from a highly excited layer of zirconium vapor and argon gas very near the cathode surface. The arc current tends to return the zirconium ions to the cathode, thus renewing its surface and resulting in a lamp life which may exceed 1,000 hours when the lamp is not modulated. A much shorter life results when the lamp is operated at a high per cent current modulation. The anode is designed for efficient cooling in order to minimize the vaporization of material from it which might contaminate the cathode.

By proper cathode design the diameter of the radiation source may be made so small as to approximate a point source. The concentrated-arc lamps may possess modulation ratios (Section 1.1.4) and brightness values comparable with those of the carbon-arc lamp while having the added advantages of nonvaporizing electrodes and a fixed position for the cathode spot.

Figure 8 shows a variety of experimental designs which have been successfully constructed, including several lamps in sizes larger than standard. Certain characteristics of the four standard lamp types are summarized in Table 5. In the standard type, the 100-watt lamp is available only in a side projection model similar to item 7 of Figure 8. The other sizes are available either in a side-projection or an end-projection model. In all of the standard types the anode consists of a metal plate with a hole through which the radiation from the cathode emerges.

Table 5. Operating data on standard types of concentrated-arc lamps.

Nominal lamp rating (watts)	Volts	Amp	Light source diameter (mm)	Brightness candles/mm² max	Brightness candles/mm² avg	Candle-power	Candle-power per watt	Life in hours	Bulb type	Base type	Max temp (degrees F) bulb	Max temp (degrees F) base
2	37	0.055	0.085	96	56	0.32	0.155	175	T5	Min, 3 pin	140	100
10	21	0.5	0.4	55	22	2.7	0.26	900	T9	Small, 8 pin	225	130
25	20	1.25	0.73	40	21	8.5	0.35	...	T9	Small, 4 pin	355	145
100	15.4	6.25	1.58	52	39	77	0.80	700	ST19	Medium, 4 pin	470	160

Cathode Construction. The cathode consists of a tantalum tube packed with finely ground fused zirconium oxide and drawn to a cored wire of the desired size. A short length of this wire is mounted in the lamp so that one end, with its exposed oxide, is $\frac{1}{32}$ to $\frac{1}{4}$ inch from the anode. When the arc is

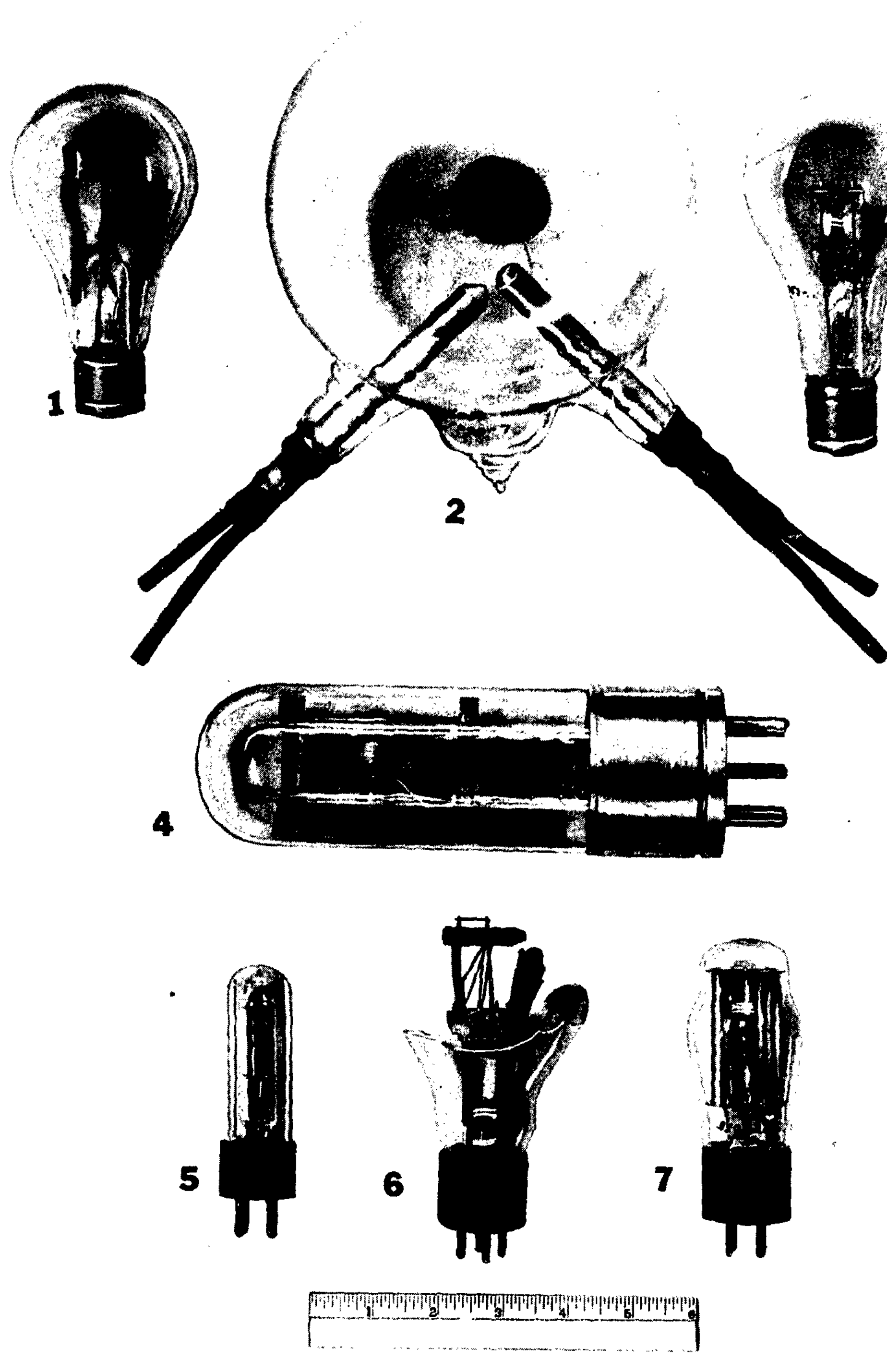


FIGURE 8. Experimental types of concentrated-arc lamps.

first struck, the oxide fuses to a hemispherical bead in the end of the wire. Tantalum is used as the sheath because of its high melting point and the ease with which it can be worked and drawn. For each lamp size this sleeve is proportioned to operate at a temperature no higher than 2000 K at the hottest point. A still higher operating temperature might result in improved efficiency for producing steady radiation but would probably be detrimental to the modulation characteristics of the lamp and to the stability of the cathode spot. The most stable and uniform operation is obtained when the cathode spot very nearly fills the activated zirconium oxide surface.

Anode Construction. The anode is made of molybdenum punched or cut from sheet stock and formed to the desired final shape in a small press. Except for the difficulty of shaping it, tungsten is an equally good anode material. The shape of the anode is not important; its dimensions are chosen only to provide adequate heat dissipation. The arc strikes to the edge of a hole, in the center of the anode, which also serves as a window for the cathode. It is found that experimental lamps rated at more than 300 watts have better characteristics if water-cooled anodes are provided.

Other Features of Construction. The radiation spectrum contains lines characteristic of the gas with which the lamp is filled. Argon and krypton are the most satisfactory gases, and the former is normally used.

The electrodes may be mounted in any position within the bulb so long as their relative orientation and spacing are properly preserved. The standard point cathode and perforated-plane anode structure lowers the breakdown potential required for starting the lamp and also results in lengthened lamp life, since the arc may operate from any point on the edge of the hole in the anode.

The surface of the glass bulb must be large enough to avoid overheating at any point and may be smaller for Pyrex or Nonex than for soft glass bulbs. Standard commercial tube- and lamp-type bulbs may be used for side-projection models, but special measures are ordinarily required to provide sufficiently good optical quality for the windows in end-projection types. The lamps may be mounted in various types of bases, the principal requirements being that they withstand the high voltages used in starting the lamps and that they be polarized. Molded Bakelite bases of the radio-tube type are preferred, such as those listed in Table 5. Prefocus bases can be provided if they are needed, for example, to preserve the alignment of an optical system when the lamp is exchanged or replaced.

Static Electrical Characteristics and Operating Circuits

The volt-ampere characteristic curve for the concentrated-arc lamp has a negative slope, just as for other well-known arcs. However, if the arc current is increased beyond the point at which the cathode spot just fills the activated zirconium oxide surface, the slope of the volt-ampere curve tends to increase to zero and may even become positive. Once the arc is established, stable d-c operation requires only that sufficient positive ballast impedance be included in the circuit to neutralize any negative resistance exhibited by the lamp over the desired operating range of current.

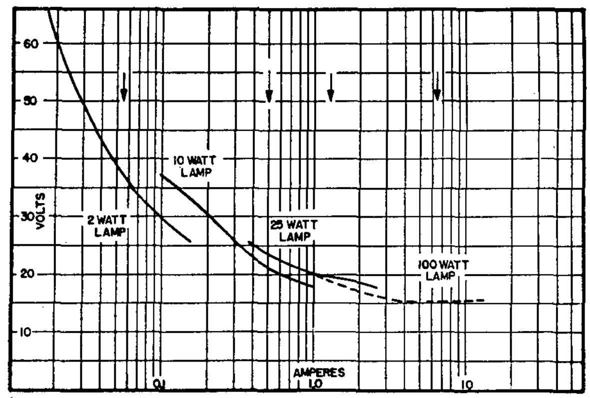


FIGURE 9. Average static volt-ampere characteristics of aged concentrated-arc lamps. Arrows indicate normal operating current.

Since the characteristics of a lamp change somewhat during its operating life, the data chosen for presentation below are average values for lamps aged sufficiently to have well-stabilized characteristics. The average static volt-ampere characteristics of the four standard lamp sizes are shown in Figure 9. Other average static characteristics for lamps of the 10-watt size, as an example, are shown in Figure 10.

The concentrated-arc lamps operate on relatively low-voltage direct current but require high-voltage starting circuits. By means of rectifier power supplies they can be started and run from an a-c source

if desired. Such power units must include a high-voltage starting supply, a low-voltage operating supply, and adequate provisions for switching the lamp from one supply to the other at the proper time.

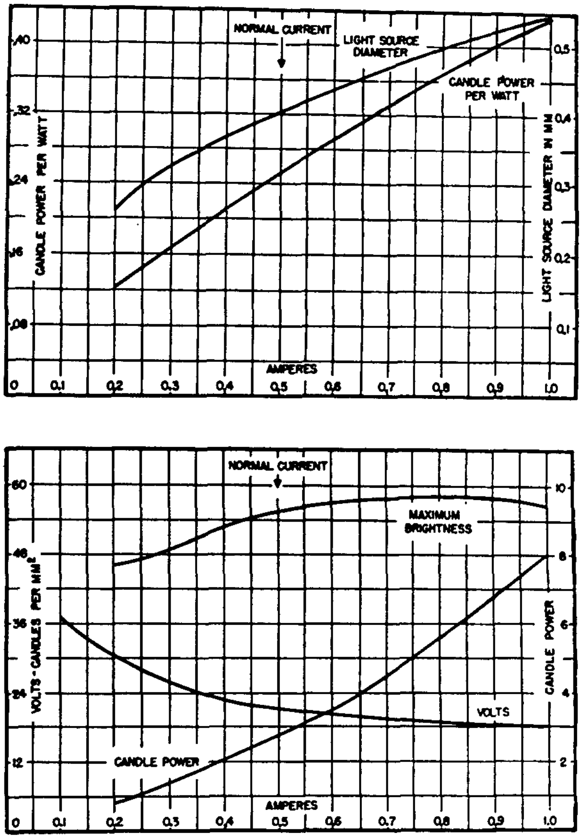


FIGURE 10. Average static radiation characteristics of aged 10-watt concentrated-arc lamps.

Starting Circuits. For different lamp sizes and designs, the breakdown voltage may vary from 500 to 1,500 volts or more. To provide consistently reliable starting, the high-voltage starting supply should have sufficient current capacity to initiate a small concentrated arc and not merely to establish a high-voltage spark discharge, since the starting current must cause the arc voltage to fall to a value equal to or less than the open-circuit voltage of the operating supply. Three methods which have been employed to start the arc are described in the following paragraphs.

In the first method, the lamp is connected to the d-c operating supply in series with the proper ballast resistance, and the output from a high-frequency spark coil is applied to the circuit. This method is often convenient in the laboratory, but is not considered satisfactory for general use, since the radio-frequency characteristics of the associated wiring may determine whether a given lamp will fire, and also the open-circuit voltage required for the d-c operating supply is likely to be higher than for other starting methods.

In the second method, the transient inductive voltage pulse obtained by interrupting the current through a choke in series with the lamp is used to break down the arc gap. The lamp then continues to operate from the same power source which energized the starting circuit. The principal advantage of this method lies in the fact that relays may be used to make the circuit automatically self-starting and to repeat the starting cycle automatically if the lamp is accidentally extinguished. However, this method is completely satisfactory only for the 2-watt lamp; for larger lamps the third method is more efficient and reliable.

The third method utilizes more expensive components and power requirements, but at the same time provides more positive and generally satisfactory starting. It consists essentially of a poorly regulated high-voltage rectifier having an open-circuit voltage of 1,000 to 2,500 volts.

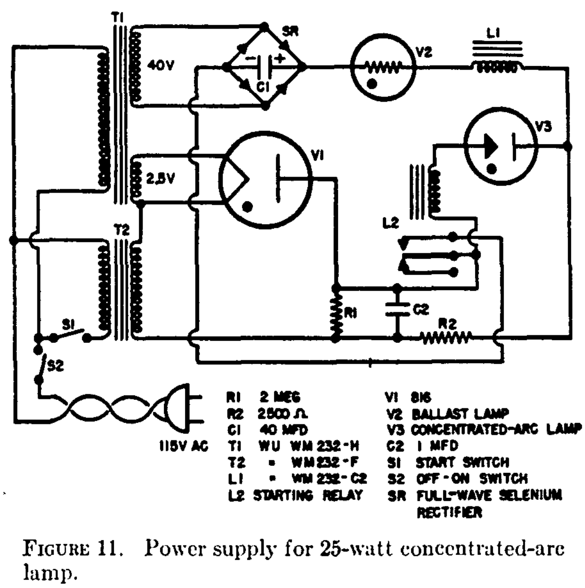


FIGURE 11. Power supply for 25-watt concentrated-arc lamp.

A representative power supply circuit for starting a 25-watt lamp and operating it from a selenium rectifier is shown in Figure 11. After the filament of the starting rectifier tube V1 has been heated by

closing the main switch S2, the starting switch S1 is closed, applying plate voltage to the rectifier tube and rectified high voltage directly to the lamp terminals. The arc gap instantly breaks down, and a current of 100 to 200 milliamperes flows through the lamp and the coil of the starting relay L2. Operation of the relay connects the output of the selenium rectifier to the lamp in parallel with the high voltage supply and the lamp current rises to its normal value of 1.3 amperes. Since the selenium rectifier current also flows through the relay coil, the relay contact remains closed and the lamp continues to operate after the starting switch is opened.

Fully automatic methods for starting the lamp and for switching over to the operating circuit may be added when necessary. The added cost and complexity of this measure are frequently not justifiable if the lamp is to be used simply as a source of steady radiation, but may be essential if it is to be electrically modulated as the radiation source for a communication system.

Operating Circuits. The concentrated-arc lamps can be operated from any d-c source capable of delivering a sufficiently smooth current at the required voltage. Except for the 2-watt lamp, an operating potential difference of about 16 to 24 volts at the lamp terminals is ordinarily adequate (see Figure 9), to which must be added an allowance of about 50 per cent for the potential drop across the series ballast impedance. The required power may be obtained from storage batteries, a motor-generator set, or a-c power with an electron-tube or a selenium rectifier. The final choice of power supply in each case will, of course, depend on the requirements of the particular application and the available facilities. The selenium bridge-type rectifier is most commonly used in the power supply units constructed by the Western Union Telegraph Company. A typical circuit for such a unit is shown in Figure 11. For the 2-watt lamp, a special a-c operated power supply has been devised [23a] in which very satisfactory starting and operating are achieved with only one transformer and one rectifier tube. This circuit also provides fully automatic starting and switch-over to continuous operation.

Because the arc acts as a negative resistance it is essential for stable operation of the lamp that enough positive impedance be included in the operating circuit to neutralize this characteristic. In general, a ballast resistance is sufficient if the voltage drop across it is about one-half of that across the arc. A rheostat with provision for manual control may be satisfactory, or a constant-current ballast tube of the type frequently used in electronic circuits may be more convenient, for example, a tube such as those manufactured by the Amperite Company. With a ballast tube of this type it is best to keep other impedances in the circuit as low as possible in order to secure maximum effectiveness of current regulation. The degree of regulation required depends, of course, on the type of power supply used and the other conditions of each specific application.

By means of specially constructed experimental arc lamps it has been demonstrated that the radiation characteristics of the cathode spot in the d-c operated concentrated-arc lamp can be duplicated by raising the cathode to incandescence either by joule heating or by electron bombardment. Many lamps of the 10-watt and larger sizes can also be operated directly from a low-frequency a-c source, the lamps acting as self-rectifiers. Ballast impedance should also be included in the circuit for this type of operation.

Static Radiation Characteristics

As shown in Table 5, the maximum brightness of the cathode spot in the standard concentrated-arc lamps is from about 40 to 100 candles per square millimeter. These values are about one-half as great as for the crater of a small d-c operated plain carbon arc, and from three to ten times as great as for incandescent tungsten filaments near 3000 K. Up to the current value at which the cathode spot completely fills the zirconium oxide surface, the size of the spot rather than its brightness is principally affected by changes in the arc current. An increase in brightness will result from still higher current, but the life of the lamp will be shortened. At current values very much less than normal the spot becomes variable in size and position. The maximum brightness is always found near the center of the spot. The lamps are not sufficiently stable either in total intensity or brightness distribution over the cathode spot to constitute a satisfactory substitute for incandescent tungsten lamps as photometric standards.

Intensity measured as a function of angle from the normal to the cathode has the distribution expected for a plane disk which radiates in accordance with the cosine law.

During the first few hours of operation the maxi-

mum brilliance of the cathode spot increases to about 130 per cent of the initial value. Thereafter the brilliance, candlepower, and cathode spot diameter all show a gradual decrease throughout the remaining life of the lamp. The life is said to be terminated when the arc is no longer concentrated, that is, when the cathode spot is dull and extended rather than white and concentrated or when the lamp can no longer be started with the standard equipment ordinarily used for this purpose. These conditions are usually caused by shrinkage or loss through vaporization of the cathode filling material. The average life is 175 hours for 2-watt lamps and 900 hours for 10-watt lamps. Individual lamps in the 25-watt and 100-watt sizes have had lifetimes up to 5,000 hours when not modulated, but sufficient data are not available to indicate an average life for these sizes. The life of a lamp operated on direct current without modulation is apparently no different for intermittent start-stop operation than for continuous operation.

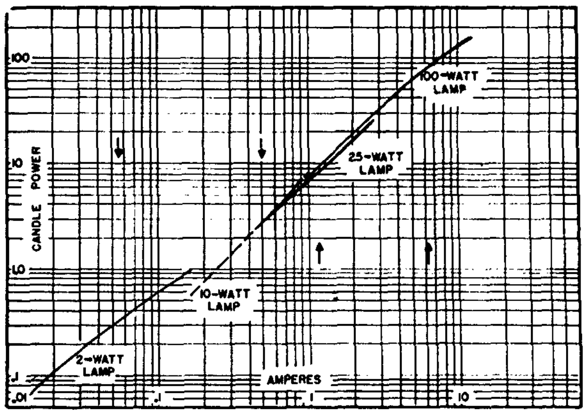


FIGURE 12. Average static candlepower characteristics of aged concentrated-arc lamps. Arrows indicate normal operating current.

Intensity versus Current and Power. As shown in Figure 12, the relationship between candlepower and current is almost linear over a very wide range of current for each lamp size. The major part of the candlepower change is due to an automatic change in the diameter of the cathode spot as the current is varied.

The efficiency of concentrated-arc lamps, measured in candlepower per watt input to the lamp (not including the power expended in the ballast impedance) as a function of current, is shown in Figure 13. The higher efficiency values for the lamps of larger size may be due to relatively lower heat losses from the activated radiating surface to the cathode supporting structures. The figures are, on the average, only about one-half as great as for incandescent tungsten lamps. Moreover, because of the spatial distribution characteristics of a disk-type radiator, the total flux from a concentrated-arc lamp is only about one-third of that from a tungsten lamp of equal hololuminous intensity, or about one-sixth of that from a tungsten lamp operated at equal power.

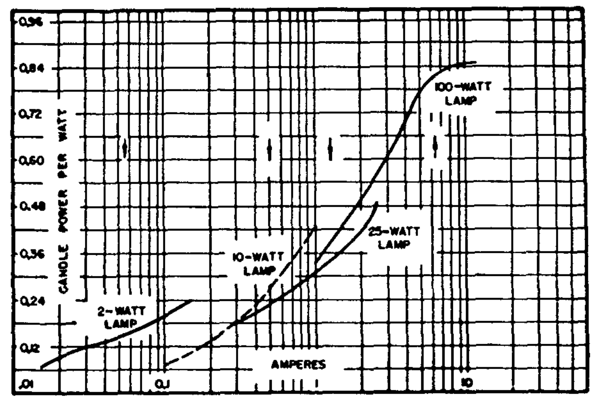


FIGURE 13. Average static luminous efficiency of aged concentrated-arc lamps. Arrows indicate normal operating current.

Spectral Distribution. A typical spectral distribution curve for the wavelength region from 0.3 to 1.0 μ is shown in Figure 14. The spectrum consists essentially of a continuum upon which are superposed spectral lines of zirconium and of the filling gas. The peak of the radiation curve occurs near 1.0 μ and the curve resembles that of a black body

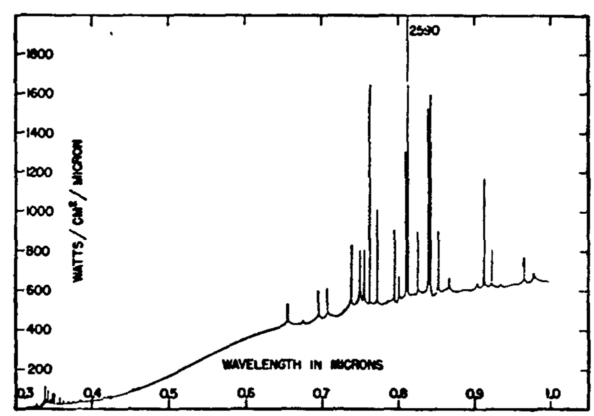


FIGURE 14. Static spectral distribution of radiation from concentrated-arc lamps.

near 2800 K, lying somewhat above the black body curve on both sides of the peak. The spectral distribution in the near infrared is thus quite similar to that for an incandescent tungsten lamp, and because of the large amount of radiation in the visible region a relatively dense filter is required to provide the security which is essential for applications in military signaling and communication systems. It has been estimated that more than 90 per cent of the total radiant energy originates from the incandescent cathode spot, in contrast to the relatively small amount which originates in the gaseous arc column.

Dynamic Electrical Characteristics

When an a-c voltage wave is impressed on the terminals of a concentrated-arc lamp through which direct current is flowing, the resulting a-c current wave lags behind the applied a-c potential wave by an angle whose magnitude depends on the impressed frequency. The modulated radiation wave in turn lags behind the current wave, but by an amount which is generally much smaller than the current voltage lag. Distortion of the radiation wave is not large for frequencies in the audio range, so that the quality of voice reception in systems using this source is determined principally by factors other than arc characteristics.

The dynamic electrical characteristics may be summarized as follows:

1. The equivalent internal impedance of the lamp is composed of a variable resistance and an inductive reactance.

2. The resistive component decreases with a decrease in the unmodulated direct-current operating value, becoming negative at low d-c values. The magnitude and sign of the resistive component also depend on the frequency of the modulating potential.

3. The inductive reactance component increases with a decrease in the direct-current operating value. The equivalent inductance is almost inversely proportional to modulation frequency, the inductive reactance being essentially independent of frequency.

4. The impedance is definitely nonlinear over the medium range of current modulation ordinarily employed.

5. The modulated radiation is almost directly proportional to the modulated current within the usual range of per cent current modulation, but lags behind it by a small phase angle which varies so slowly with frequency as to be of little importance in communication systems.

Typical curves showing the dependence of the electrical characteristics on frequency for lamps operated at rated d-c values and at 50 per cent current modulation are given in Figure 15, which refers specifically to the 10-watt lamp. The effective impedance of the lamps varies from a few hundred ohms in the 2-watt size to only a few ohms in the

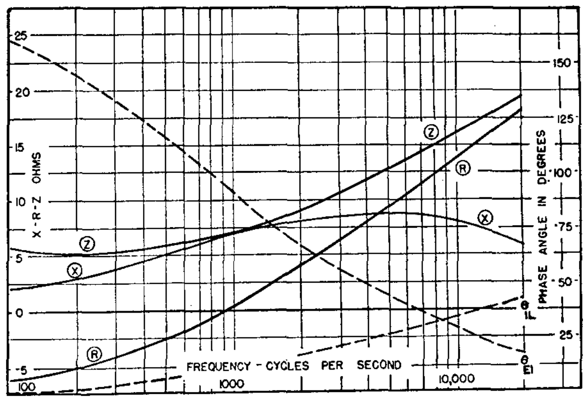


Figure 15. Impedance and phase characteristics of 10-watt concentrated-arc lamps.

100-watt and larger sizes. It is of interest to note that a minimum occurs in the curve of impedance versus frequency; the frequency at which it occurs becomes lower as the size of the lamp is increased. It is thought that the lamp may have negative resistance at some much higher frequency range also, since self-sustained radio-frequency oscillations have sometimes been found to exist in the lamp circuits.

Modulating Circuits. A sine-wave modulating current will produce essentially a sine wave of radiation from the concentrated-arc lamp, the only distortion being the relatively unimportant phase distortion. A sine wave of voltage will not produce this result, however, since the volt-ampere characteristic is nonlinear in both amplitude and phase. Moreover, the arc is limited in the amount of current it can pass because of the limitations of heat dissipation and current saturation. When overdriven it will to some extent rectify the applied signal, causing an additional d-c component to flow and diminishing slightly the d-c terminal voltage.

When stability of operation and low distortion

are important, as for use in a communication system, the following general requirements should be observed in the operating and modulating circuits.

1. The effective impedance in series with the lamp, including the effect of other circuits in parallel with the lamp circuit, should always be greater than any instantaneous negative impedance presented by the lamp.

2. The best linearity between the electric input and the modulated radiant output is obtained when the lamp is modulated by a constant-current generator. Such a generator, having infinite internal impedance, also provides a maximum of stability.

3. The electric modulation source should be capable of supplying the peak instantaneous modulation power over the desired frequency band to a load having distinctly nonlinear characteristics and yet not be overloaded itself.

4. The possibility of extinguishing the arc by overmodulation can be minimized by removing the low frequencies for which the possible period of overmodulation is equal to or greater than the time in which the arc may be extinguished, or it can be completely eliminated by limiting the amplitude of the signal.

5. The d-c operating supply should be sufficiently smooth to prevent the introduction of undesired modulation components or frequencies.

The impedance of the 2-watt lamp is sufficiently high so that it can be successfully modulated in the plate circuit of a vacuum tube, the modulating voltage being applied to the grid. The larger lamps do not permit modulation by this method.

The most economical and generally satisfactory method of modulating the lamp is to apply the modulating current directly through the lamp and not through the ballast resistance and other circuit

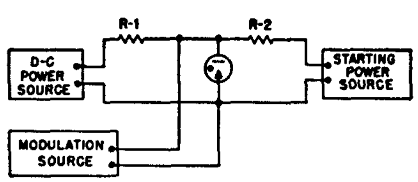


FIGURE 16. Schematic method of modulation.

components. This basic method is shown schematically in Figure 16; its successful application depends on keeping the shunt impedances of the starting and operating circuits high as compared with the impedance presented by the lamp. In practice it is necessary to modulate lamps larger than the 2-watt size through an impedance-matching power transformer and a series blocking condenser. The actual power required to modulate the lamp may vary from 50 to 100 per cent of its normal d-c power rating, depending on the size of the lamp and the operating conditions which it is desired to meet.

Characteristics as a Source of Modulated Radiation

Radiation from the concentrated-arc lamp appears to consist of the following three parts which are listed according to the total radiation emitted: continuous radiation from the incandescent cathode spot, line radiation from the excited gas and vapor, and some continuous radiation, at least in the shorter wavelength visible regions, originating in the excited gas and vapor. As would be expected on this basis it is found that the modulation characteristics of the emitted radiation depend upon its wavelength, upon the modulating frequency, and upon whether average characteristics of the entire radiation emitted by the lamp are investigated or only the characteristics of that portion of the radiation which originates in the arc stream or at a selected region of the cathode.

A rather detailed experimental investigation of the modulation characteristics has been made from which the following conclusions were drawn.[24a] A part of the radiation, most pronounced in the blue and ultraviolet regions of the spectrum, responds almost instantaneously to changes in the arc current. A considerably larger part, whose relative value also varies with wavelength, follows the arc current with a time lag of the order of 10^{-4} second. A third part, especially prominent in the infrared region and believed to arise primarily as thermal radiation from a sharply defined incandescent spot on the cathode surface having a relatively low true temperature of the order of 2000 K, is not subject to appreciable modulation over the useful range of audio frequencies. The relative amount of infrared radiation which cannot be modulated at useful frequencies is thought to depend critically on the thermal insulation of the material forming the thin, activated surface of the cathode, and on the composition and behavior of this material under bombardment by ions from the arc column. Presumably this radiation can be modulated only by changing the temperature of the cathode surface, the thermal inertia of which

is too great to permit appreciable modulation within the audio-frequency range.

The spectral distribution of modulated radiation from the concentrated-arc lamp at a modulation frequency of 1,000 cycles per second is shown in Figure 17. The relative dependence of the modulated intensity upon wavelength is illustrated by comparing the curve of Figure 17 with the static spectral distribution curve of Figure 14. The data for Figure 17 were obtained by using an a-c amplifier

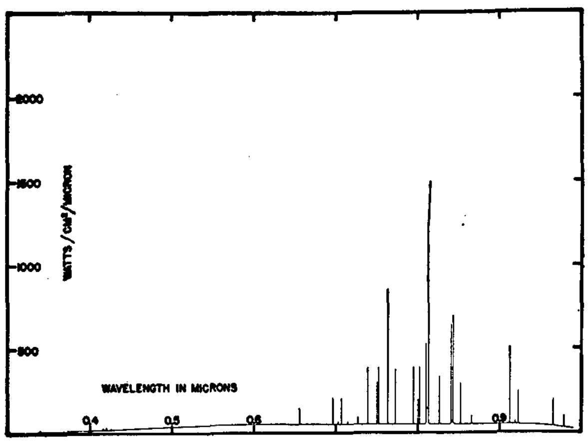


FIGURE 17. Spectral distribution of 1000-cycle modulated radiation from concentrated-arc lamps.

following the photoelectric radiation detector so that the unmodulated radiation at each wavelength was not measured. A series of similar curves obtained for other modulation frequencies show that as the modulation frequency is increased the amplitude of the continuum, which originates primarily from the cathode, decreases by a much larger factor than the amplitude of the spectral lines, which originate in the cathode glow region. A high modulation ratio for the spectral lines exists throughout the entire audio-frequency range, the upper frequency limit for successful modulation presumably being determined by the deionization time of the gas.

The dependence of the modulation ratio upon frequency and upon spectral region is shown for one lamp in Figure 18. The ultraviolet curve was obtained by using a combination filter (Corning 430 with Corning 584) which has a transmission peak at about 3600 Angstrom units, in conjunction with a photomultiplier tube (RCA type 931) having an ultraviolet-sensitive antimony cathode. The other curves represent the response of an infrared-sensitive cesium-cathode phototube to the modulated component of the radiation transmitted by the following filters: Corning 430 (blue), Corning 241 (red), and Polaroid XR7X (infrared).

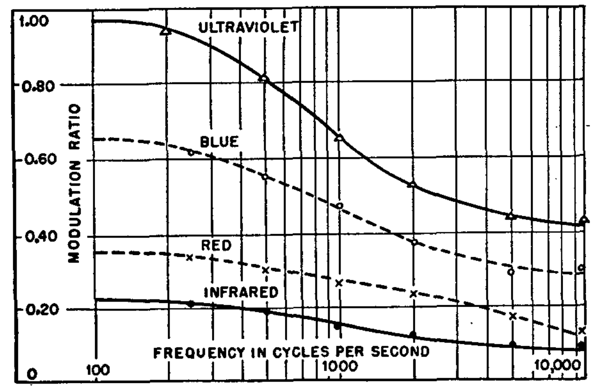


FIGURE 18. Modulation ratio *versus* frequency for different wavelength regions of concentrated-arc radiation.

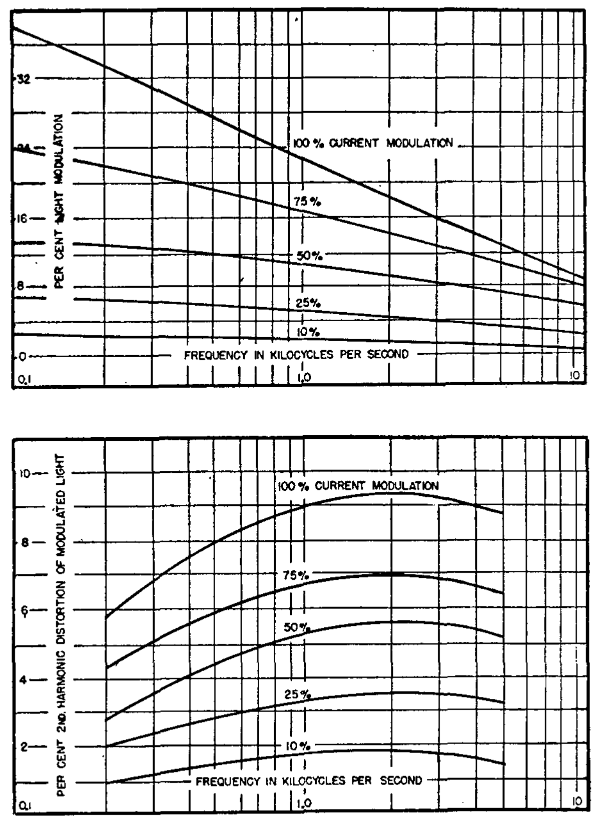


FIGURE 19. Modulation characteristics of 10-watt concentrated-arc lamps with reference to a cesium-surface detector.

The modulation characteristics of the 10-watt concentrated-arc lamp, as an example, are shown on a somewhat different basis in Figure 19. These

curves were obtained by using the entire radiation from a lamp with no filter interposed and with an infrared-sensitized cesium-cathode phototube as the detector. The per cent modulation of the emitted radiation at 100 per cent current modulation is, by definition, the modulation ratio. The per cent modulation of the radiation shows a decrease as the lamp size is increased, but, because of the greater quantity of radiation emitted by the larger lamps, the total modulated radiant energy is considerably greater for the large than for the small lamps. The lower graph of Figure 19 shows the percentage of the modulated radiation having the second-harmonic frequency. The distortion of the modulated radiation which results from the lack of an accurately linear relationship between lamp current and emitted radiant energy has been found to consist largely of this component, and increases with an increase in modulating frequency, per cent current modulation, and lamp size. By limiting the current modulation, the distortion can ordinarily be limited to a range within the permissible limits for usual audio-frequency amplifier practice so that it does not perceptibly affect the overall fidelity of a communication system.

It is seen, therefore, that the per cent modulation of the emitted radiation may vary over a rather wide range, depending upon the exact conditions in which the lamp is used. For certain special applications in which only a small amount of radiant flux having the highest possible per cent modulation is desired, a lens and slit arrangement may be used to isolate that portion of the radiation which originates from the cathode glow or from the center of the cathode spot. The per cent modulation under some conditions may be 50 per cent greater for lamps filled with krypton than for lamps filled with argon. Very promising results have also been obtained in experimental lamps filled with gas at a pressure of 10 to 15 atmospheres instead of the usual one atmosphere and by the use of especially designed experimental cathodes which will not be described here. Experimental variations in anode construction have also been investigated. Although some of these measures result in lamps of increased brilliance and higher radiant efficiency or modulation efficiency, they have not yet been successfully developed to a point suitable for application in large-scale production.

Life of Lamps when Modulated. When the current through a lamp is modulated, the life of the lamp may be considerably reduced, probably due to the loss of zirconium vapor from the cathode glow region during the portion of the modulation cycle in which the cathode is least negative. The amount by which the lamp life is reduced apparently depends upon the average value of the direct current and upon the waveform, frequency, and amplitude of the modulating current, particularly if the polarity applied to the lamp is actually reversed during any portion of the modulation cycle. The exact nature of the dependence of lamp life upon these factors is not known, but under some conditions the life has apparently been reduced by as much as 90 per cent.

Applications in Wide-Beam Optical Systems

Because of its small diameter and high brilliance, the cathode of a concentrated-arc lamp constitutes an ideal source for projecting a narrow beam of radiation which can be electrically modulated for voice or code communication purposes. When the cathode is located at the focal point of the projection system, the angular spread of the beam is approximately equal to the angle subtended by the cathode spot at the vertex of the reflector or the optical center of the lens or equivalent lens system. Thus for a system having a focal length of 8 inches, the value of the cathode spot diameter shown in Table 5 for the 25-watt lamp corresponds to a computed angular beam spread of only about 0.2 degree.

Although the lamps have been used in narrow-angle projection systems by other agencies, their principal application within Section 16.4 occurred in the early stages of development of the type E infrared voice and code communication system,[24] for which a beamwidth variable between 15 and 40 degrees was originally requested (see Chapter 4). The problem of redistributing radiation from what is essentially a point source into a fairly uniform beam having a spread of this order of magnitude is rather specialized and has been treated in detail elsewhere.[26]

Some of the problems associated with the production of a wide-angle beam from a very small source are the following: (1) since the total flux available from the source is limited by its small size no matter how high its brilliance, and since for any given total flux available from the source the intensity available at a receiver will vary inversely

as the solid angle into which it is spread, it is essential that the greatest possible fraction of the flux emitted by the source be collimated within the specified angular limits of the beam and that the source and its mountings obscure the smallest possible portion of the collimated beam; (2) aberrations in classical idealized optical systems utilizing, for example, surfaces of revolution having conic sections, give rise to nonuniformities of intensity across the beam; (3) the small size of the source demands extraordinarily high precision in the preparation of the reflecting or refracting surfaces since an irregularity in the beam pattern caused by an imperfection in the optical surface cannot be smoothed over by flux originating from an adjacent area of the source, as is the case with an extended source.

The possibilities of various types of optical systems have been investigated both theoretically and experimentally. With the 100-watt concentrated-arc lamp as the source it has been found possible to produce a rectangularly shaped beam having angular dimensions 18x8 degrees and with a sufficiently uniform intensity distribution to be satisfactory for communication and signaling systems. In the most compact and efficient system devised for this purpose (see Chapter 4) the source is mounted, facing in the direction of the emergent beam, at the focus of a spun Alzak parabolic reflector having a focal length of 0.6 inch, 6 inches in diameter and 7 inches deep. An $f/1.2$ plano-convex lens is used to collimate radiation that would otherwise pass uncollimated out the front opening of the reflector. Over the front of the reflector is placed an 18x8-degree spread lens of a type which is available, for example, from the Holophane Company, Newark, Ohio. The multiple-facet construction of the spread lens serves not only to give the desired divergence but also smooths out the irregularities which would otherwise exist due to the surface imperfections in commercially available optical elements. More complete details of this and related systems and a general discussion of source and transmitter optics and of other factors in relation to the performance characteristics of complete communication systems are given in Chapter 4 and elsewhere.[24b,27]

The beam candlepower of the 18x8-degree transmitter described above, using the 100-watt concentrated arc as the source, is approximately 5,000 equivalent holocandles with reference to a cesium-surface vacuum phototube.

Infrared Filters for Concentrated-Arc Lamps

Since the spectral energy distribution of radiation from concentrated-arc lamps consists principally of a continuum with a distribution similar to that for the radiation from incandescent tungsten lamps, the infrared filters required to give them sufficient visual security for military purposes are quite similar to those required for use with tungsten lamp sources. Basic problems and general considerations pertaining to infrared filters are outlined in Chapter 2, while those selected for use in specific near infrared systems are indicated in Chapters 4, 5, 6, and 7.

The ehT values of filters measured with reference to the modulated radiation from electrically modulated concentrated-arc lamps are considerably lower than the values for the same filters with reference to radiation from unmodulated or mechanically modulated tungsten lamps for two reasons. First, the near infrared component of concentrated-arc radiation is relatively smaller than for incandescent tungsten radiation, the arc radiation being richer in energy at visible wavelengths. Second, as shown by Figure 18, the modulation ratio at different wavelength bands decreases with increasing wavelength, so that an infrared filter apparently discriminates more strongly against the modulated infrared components than its spectral transmission curve, or experimental tests made with an unmodulated lamp, would indicate.

The ehT values of three representative infrared filters with reference to radiation from an arc fully modulated at 1,500 cycles per second, as measured by two different infrared detectors, are shown in Table 6. Also included for each of these filters is the calculated visual range of a transmitter having an intensity of about 5,000 holocandles in the absence of a filter, such as the one described in the preceding section. Corresponding ehT° values for the Polaroid XR3X41 filter, with reference to radiation from an incandescent tungsten source at a color temperature of 2848 K, are about 27 per cent for the cesium-cathode phototube and about 45 per cent for the thallous sulfide photoconductive cell (see Chapter 3).

Discussion

Concentrated-arc lamps in the four standard sizes which are now commercially available constitute an interesting and potentially valuable source of

near ultraviolet, visible, and near infrared radiation. The lamps have been successfully used for a number of applications requiring a high-intensity, concentrated radiation source. The feasibility of constructing lamps up to 1,000-watt ratings using water-cooled electrodes has also been demonstrated, and experiments initiated before the conclusion of NDRC sponsorship indicated the possibility of further improvements in radiation efficiency and electrical modulation characteristics.

TABLE 6. Effective holotransmission of various filters and calculated visual range of a 5,000-holocandle transmitter using the concentrated-arc lamp.

Filter	ehT for modulated radiation component from arc fully modulated at 1,500 cycles		Calculated visual range (yards)
	Gas-filled C, phototube	Thallous sulfide cell	
Wratten 87	0.35	0.55	8,000
Polaroid XR3X41	0.06	0.16	70
Polaroid XR7X25	0.03	0.14	35

A great many scientific questions regarding the operation of concentrated-arc lamps and the explanation of their characteristics remain unanswered and should be explored in greater detail. For example, estimates for the temperature of the cathode surface based on (1) the spectral distribution of the radiated energy, (2) Stefan's law and the total energy radiated, and (3) the electron emission needed to maintain the arc using the work function of metallic zirconium which might be produced by reduction of the oxide, differ by nearly 1000 K. Other questions immediately arise, such as whether the thin activated layer at the cathode spot is molten or solid during operation; the origin of the continuum, its spectral distribution, and its relationship to other continua; the possible relation between the semiconducting properties of the cathode surface and the time lag in the emitted radiation; and the frequently contradictory results of measurements made in different laboratories on lamp life, modulation ratio, spectral distribution of modulated and unmodulated radiation, etc.

Although the possibility of using concentrated-arc lamps in wide-angle modulated-beam communication systems was successfully demonstrated, a less concentrated type of source, such as the cesium-vapor lamp described in the following section, is generally to be preferred for this purpose.

1.3.3 The Cesium-Vapor Lamp

The cesium-vapor lamp was developed by the Lamp Development Laboratories of the Westinghouse Electric Corporation under Navy contract and was made available in 1944 for NDRC use as a source of near infrared radiation. Two different sizes of this lamp have been standardized in cooperation with Northwestern University under Contract OEMsr-990 for use as the source in infrared communication and signaling systems [24,28] developed by that contract (see Chapter 4). It is understood that the development of additional sizes of this lamp for other applications has been initiated.

The radiation emitted by this lamp originates in the column of a low-pressure arc discharge in cesium vapor. About 20 per cent of the input power is radiated in the two cesium resonance lines at wavelengths of approximately 0.85 and 0.89 μ. Since most of the radiation originates in the arc column, a much higher modulation ratio may be achieved than is possible for a concentrated-arc lamp. The visual security required for military applications may be achieved with a much less dense filter than is needed for sources which have a high-intensity continuous spectrum. The electrical characteristics and methods of operation are very similar to those described in Section 1.3.2 for concentrated-arc lamps and will be described largely by reference to that section.

Lamp Design and Construction

The details of construction of the 90-watt type CL–2 cesium-vapor lamp are shown in Figure 20. The same general type of construction is used in other sizes of this lamp, for example, the 50-watt lamp employed in the aircraft communication systems [28] described in Chapter 4. The inner bulb is made of heat-resistant glass (Corning No. 705) coated with a special alkali-resisting glaze to prevent corrosive attack by the cesium vapor. It contains a small amount of cesium metal and is filled with neon or other rare gas at a low pressure. The electrodes consist of coiled tungsten filaments, spaced about three inches apart, by means of which the lamp is preheated for 1 to 3 minutes and the cesium metal is vaporized. The cathode filament is

coated with a barium-strontium oxide mixture to afford the copious emission of electrons needed to maintain the arc. The outer envelope is a T–16 bulb, evacuated to reduce heat losses and mounted in a standard 4-pin base.

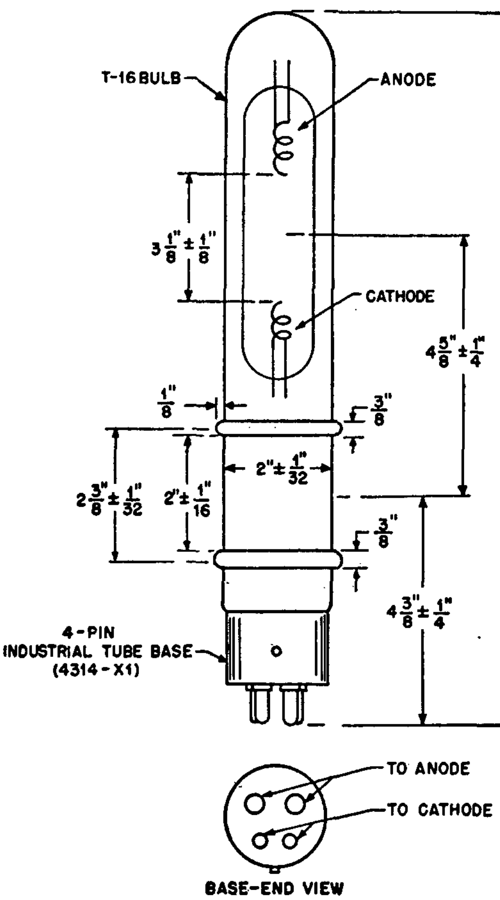


FIGURE 20. The Westinghouse type CL–2 cesium-vapor lamp.

Electrical Characteristics and Operating Circuits

Since the arc is maintained in a metallic vapor, the electrical and radiative characteristics are both complicated by thermal time-lag effects in that the instantaneous characteristics are dependent on the immediately previous thermal history of the lamp. The 50-watt lamp, which has an electrode spacing of 1.5 to 2 inches, is normally operated at about 12 volts and 4 amperes direct current. The type CL–2 lamp consumes about 90 watts when operated at 5.5 amperes direct current. The static volt-ampere curve is essentially flat from 1 to 8 amperes. The average voltage at the lamp terminals over this range of current may vary between 11 and 25 volts, not only for different lamps but also for a given lamp over its lifetime. The circuit requirements for stable d-c operation are essentially the same as for concentrated-arc lamps. The static radiant intensity of the lamp is approximately proportional to the direct-current value when thermal equilibrium is attained. Presumably the operating temperature, electric power input, and radiant output might be increased by continuously heating the starting filaments. However, continuous operation of the filaments from the normal 2.5-volt a-c supply was found to introduce a 120-cycle ripple in the radiation output large enough to be objectionable in a communication system.

The dynamic internal impedance of the 90-watt lamp at 1,500 cycles per second is of the order of 1.6 ohms when the lamp is operated at 5.5 amperes direct current. It consists principally of a resistive component, plus an inductive reactance of the order of 0.4 ohm. The variations of impedance with frequency and with the magnitude of the direct current are identical in nature with those for concentrated-arc lamps, but, in many respects, the electrical behavior is considerably superior. The cesium lamp is much more stable and can be operated up to 100 per cent current modulation without danger of being extinguished. Moreover, the dynamic voltage-current relation is very nearly linear over a much larger current modulation amplitude than for concentrated-arc lamps, and the radiant energy emitted is essentially proportional to and in phase with the arc current over the entire audio-frequency communication band. A considerable improvement in the tone quality and intelligibility of voice communication therefore results from the use of this lamp.

Because of the long filament and lead structure of the lamp a considerable variation in its performance may result from different modes of connecting the modulating circuit to the electrodes. The most uniform performance from different lamps is obtained by connecting the modulating current to the center taps of the filament transformers. The principles of operation and the characteristic features of the modulating circuits required for optimum performance are identical with those already described for the concentrated-arc lamp.

Starting Circuits. The starting of the cesium-vapor lamp is affected by several factors. The cesium

vapor condenses on the inside of the bulb when the lamp is inoperative so that, because of time-lag effects, its vapor pressure depends much more critically upon the recent thermal history of the lamp than upon the pressure of the inert filling gas. The condensed cesium may, under certain circumstances, partially or completely short-circuit the arc gap for starting purposes. Some of the cesium originally available is gradually lost by combination or absorption in the bulb, and the condition of the starting filaments with reference to electron emissive properties is also important.

It is therefore impossible to enumerate the optimum starting conditions for all circumstances. However, it is found that reliable starting is attained in most applications by preheating the filaments for one minute and then applying 400 volts alternating current or 500 volts direct current. The starting arc current should lie preferably between 0.5 and 1.0 ampere. The filament heating source is disconnected once the arc is established on the operating power supply. The switch-over requirements and the general types of circuits which can be used for starting and operating the lamps are quite similar to those already described for use with the concentrated-arc lamp.

Radiation Characteristics

Due to the low intensity of the spectral lines emitted in the visible region, the visual intensity of the bare 90-watt cesium lamp is only about 5 candles. With reference to a cesium-surface detector, however, the intensity is from about 90 to 150 equivalent holocandles for the 90-watt lamp, and about 70 holocandles for the 50-watt lamp. The visual output apparently varies at some power of the lamp current greater than unity, so that the luminous intensity of the lamp increases during modulation even though the average current remains constant. This visual effect is entirely eliminated if the lamp is viewed through a relatively light infrared filter such as Wratten 87. The spatial intensity distribution is essentially that to be expected from the sine distribution law for a linear source, and the total flux emitted is about three times as great as that from a plane disk source of equivalent intensity, such as a concentrated-arc lamp, for which the cosine intensity distribution law is followed.

Being concentrated principally in the two cesium resonance lines at an average wavelength of about 0.87 μ, the useful infrared radiation from the lamp is essentially monochromatic. The ehT values of filters for cesium lamp radiation are therefore very close to the spectral transmission values of the filters at this wavelength and are almost independent of whether a cesium-cathode phototube, a thallous sulfide photoconductive cell, or some other type of infrared photodetector is used.

The useful near infrared radiation originates exclusively in the arc column and has a very small time lag behind the modulating current. A high modulation ratio is therefore to be expected; its average value is found to be about 0.92 from 200 to 5,000 cycles per second, decreasing at higher frequencies to a value of about 0.70 at 10,000 cycles. Since the useful modulated infrared radiation is almost monochromatic, the modulation ratio is essentially independent of whether or not the source is covered with a filter.

After a few minutes of operation to permit stabilization, the arc becomes a fairly well-defined cylindrical column, about one-half inch in diameter, which may be somewhat bowed due to thermal convection currents. After a few hours of operation a brownish stain begins to appear on the inner bulb, probably due to a reaction of the cesium with the glass. This may eventually reduce the visual intensity of the arc by a factor of three or more without appreciably affecting the intensity of the near infrared radiation. The construction and operating characteristics of the lamp are similar to those of the familiar sodium-vapor lamp so widely used as an efficient, monochromatic source for visual illumination.

Spectral Energy Distribution. Since the lamp is normally operated with the power to the starting filaments cut off, a well-developed cesium line spectrum constitutes its principal radiation in the visible and near infrared regions. Additional energy is, of course, radiated in a thermal continuum having an energy distribution centered at much longer wavelengths, corresponding to the relatively low operating temperatures of the electrodes and the lamp envelope. The relative amount of energy radiated in various wavelength regions is shown in Table 7. Only two strong spectrum lines occur in the blue region, with the result that visual security is achieved with a filter of much lower opacity than would be required for a source of equivalent holocandlepower having a continuous spectrum. The sec-

ond band listed includes the resonance lines, which contain most of the useful near infrared radiation. The experimental measurements were made with a vacuum thermocouple enclosed in a glass bulb, using a series of filters having different cutoff wavelengths. Although certain idealized assumptions were made in computing the values given in the table, the results are certainly correct as to order of magnitude.

TABLE 7. Distribution of energy radiated by the cesium arc.

Wavelength region (microns)	Per cent of total energy
0.3 – 0.78	3
0.78 – 0.9	22
0.9 – 1.4	5
1.4 – 3.5	11
Beyond 3.5	59 (remainder)

LIFE TEST RESULTS

Accelerated life test data were obtained at Northwestern University with the lamps operated on a continuous start-stop cycle in equipment especially constructed for this purpose. The sequence of operations during this test was as follows:

1. Preheat the filament for 5 minutes.
2. Start the lamp from a 480-volt, 0.5-ampere d-c starting circuit.
3. Operate 6 minutes at 5.3 amperes direct current.
4. Operate 49 minutes at 5.3 amperes direct current with 3.6 amperes (rms) modulating current at 1,500 cycles per second superposed, corresponding to 95 per cent current modulation.
5. Allow the lamp to cool for one hour before repeating the above cycle of operations.

In this test the frequency of starting the lamp is greater than would occur in usual field practice, and the per cent current modulation is higher than average speech modulation would require by a factor of two to four. In practical use the lamps are ordinarily operated at a stand-by current of one ampere instead of being allowed to cool completely before being restarted. The results of these tests should not be interpreted as applying directly to any other operating conditions, but they are indicative of the order of magnitude which can be expected for lamp life.

Thirty-eight type CL-2 90-watt lamps were tested in this manner, including one lamp which was initially faulty. The life was found to vary from 0 to 380 hours. The shortest life of a lamp successfully started on the cycle was 2 hours. One half of all the lamps tested were expended at or before 65 hours.

Lamps may fail in one of two ways. (1) A crack may develop in the inner bulb, usually near the anode, with the result that the arc can no longer be started at all, or the leakage of gas from the inner bulb will permit an arc to start between the leads in the outer bulb and melt them. (2) If no crack develops, the lamp is considered to have failed when all the cesium is used up. The anode then becomes brilliantly incandescent and produces a discolored bulge in the inner bulb. Although a lamp may remain operable with the residual gas for many hours after this occurs, its electrical and radiative characteristics are so altered that it is of little value.

APPLICATIONS IN OPTICAL SYSTEMS

The total flux emitted by a linear cesium lamp source is about three times that from a plane disk source (such as a concentrated-arc lamp) having equivalent hololuminous intensity in directions perpendicular to the line and plane, respectively. Nevertheless the linear extent of the arc is so great that it is difficult to collimate a high percentage of the emitted flux within a beam width approximating 20 degrees. Although a higher flux-gathering efficiency can generally be obtained with reflectors than with lenses, the efficient use of reflectors is rendered more difficult by the fact that the source is so large (2 to 3 inches long by ½ inch in diameter, and is, moreover, not transparent to its own radiation.

For the 90-watt lamp, the most economical, efficient, compact, and simple optical system is that adopted for the type E transmitter[24c] (see Chapter 4). The lamp is mounted axially in an Alzak-surface aluminum reflector 7 inches deep, approximately parabolic with an aperture of 14 inches and a focal length of 1.75 inches. The width of the resulting beam is somewhat smaller than was originally desired, being approximately 13 degrees between the points corresponding to one-half of the peak beam intensity; the peak hololuminous intensity of the transmitter measured at the center of the beam is 40 to 45 times that of a bare lamp, dropping to about ten times at 10 degrees from the axis of the beam. About 30 per cent of the emitted flux misses

the reflector entirely while another 20 per cent is lost at the reflecting surface. The remaining 50 per cent of the total flux is projected within a cone of 60 degrees total angle. About 33 per cent of the total is projected within a 30-degree cone and about 22 per cent within a 20-degree cone. When the desired beam width is only about 20 degrees, a somewhat shorter arc would result in a higher optical efficiency value for this type of mounting.

In the communication systems for aircraft[28a] using the 50-watt lamp, a similar method of mounting was used in the plane-to-ground transmitter unit (see Chapter 4). In the interest of compactness a reflector 3 inches deep having a 7.25-inch diameter and ⅞-inch focal length was used. The width of the beam between the points of one-half of the peak beam intensity is 16 degrees and the peak hololuminous intensity of the transmitter measured at the center of the beam is 18 times that of a bare lamp. The peak beam intensity with reference to a cesium-surface detector when no filter is interposed is about 1,400 equivalent holocandles. Other transmitter units in which a still wider beam was desired were constructed by using combinations of plane mirrors, with a corresponding reduction in the peak beam intensity. Details of these units may be found in the references given above.

Infrared Filters for the Cesium-Vapor Lamp

The general characteristics of infrared transmitting filters are treated more fully in Chapter 2, while the operating characteristics achieved in communication systems using certain specific filters with the cesium-vapor lamp are outlined in Chapter 4. The basic theoretical considerations from which the optimum transmission characteristics of a filter may be predicted in attempting to meet specifications on visual security and operating range for a particular transmitter and receiver combination are given in detail elsewhere.[24d,29]

Because the cesium-vapor lamp emits a line spectrum rather than a continuum, the numerical relation between its visual and holo intensity with reference to a near infrared radiation detector is quite different from that for an incandescent tungsten source or a concentrated-arc lamp. This difference is necessarily reflected in the choice of an optimum filter for the two types of source. Since most of the radiation that is useful for infrared communication systems is concentrated at 0.85 and 0.89 μ, it might appear that the ideal filter for the cesium lamp would transmit all of the radiation at these wavelengths and none at the shorter wavelengths which contribute little to the communication range but much to the visual effect. Even with this supposedly ideal filter, however, the 0.85-μ resonance line alone would make a sufficiently large contribution to the visual range so that the security requirements for communication systems (about 400 yards or less) would not be met by a transmitter of sufficiently high holo intensity to provide the desired communication range. Although the 0.89-μ resonance line makes, on an equal energy basis, an equal contribution to the range of a communication system, it makes a much smaller contribution to the visual range because of the rapid decrease in eye response between these wavelengths (see Chapter 2). A filter having an ideally sharp cutoff between the two resonance lines, so that no radiation from the 0.85-μ line and 100 per cent of the radiation from the 0.89-μ line would be transmitted, would have an ehT value of about 40 per cent with reference to a cesium-surface detector, while the visual range would be only about 10 per cent of the value which would exist if both resonance lines, but no radiation of shorter wavelength, were fully transmitted. Thus a sharp cutoff in the desired wavelength region can contribute materially to the performance of a system utilizing the cesium-vapor lamp.

The transmission curve of any actual filter rises gradually over a fairly wide wavelength band from zero to the maximum transmission value. It is possible to get a much steeper curve with organic dyes which may be incorporated in filters of the plastic resin type than with the pigments which can be incorporated in all-glass filters. Plastic filters developed by Polaroid Corporation under Contract OEMsr–1085 and Ohio State University under Contract OEMsr–987 (see Chapter 2) are found to have about equally favorable characteristics for use with the cesium-vapor lamp. It is important that the transmission cutoff lie between 0.81 μ, the upper wavelength limit for lines present in the cesium-lamp spectrum which contribute much more strongly to the visible range than to the operating range, and 0.85 μ, the wavelength of the shorter of the two resonance lines in which most of the energy useful for infrared communication purposes is transmitted.

It should also be recalled that, because of the essentially monochromatic quality of the near infrared

radiation from the cesium lamp, the ehT value of a filter for this radiation is essentially the per cent transmission of the filter at a wavelength of approximately 0.87 μ and is therefore essentially independent of what near infrared detector is used. In Table 8 are shown the transmission values of certain filters for cesium lamp radiation, together with the visual range of a type E transmitter when covered with each of these filters. The last two types listed are recommended for securing optimum performance of a system utilizing the cesium lamp with the "nonideal" filters which are actually available while maintaining the highest feasible degree of security for military operation. Details concerning the measurement of visual range may be obtained from the references given above. Other considerations which must affect the choice of a filter for military equipment, such as mechanical strength, shock resistance, and weathering characteristics, are mentioned in Chapter 2.

TABLE 8. Transmission (ehT) of various filters for cesium-lamp radiation and visual range of the type E transmitter.

Filter	Transmission (ehT)	Visual range (yd)
Corning glass, 3.2 mm, 2566	0.31	500
OSU resin plastic, early sample	0.59	700
Polaroid sandwich, polyvinyl alcohol	0.80	700
OSU resin plastic, latest sample	0.80	700

1.4 GENERAL DISCUSSION AND RECOMMENDATIONS

In addition to those discussed above, there exist other well-known sources of infrared radiation such as the carbon arc and the mercury-vapor arc lamps. Both of these types were given preliminary consideration and experimental trials for military applications in the early stages of the NDRC program. For non-image-forming military applications in detection, ranging, recognition, and code or voice communication to which the near infrared work of Section 16.4 was largely confined, they were found to be inferior in one or more respects to the types of sources already described, upon which the program of further intensive development was, therefore, concentrated.

The properties of tungsten lamps are well known and have been intensively exploited. Incandescent lamps will undoubtedly constitute in the future, as they have in the past, a most important type of source for visible and near infrared radiation, although it seems unlikely that further major advances will be made in improving their operating characteristics and mode of operation. The concentrated-arc lamp, whose radiation characteristics are in many respects similar to those of the incandescent tungsten lamp, is a development of potential importance for certain specialized applications. Additional improvements in this type of source may be possible, and this fact should be borne in mind in connection with future military equipment problems. For some purposes, especially wide-angle, near infrared communication systems, the cesium-vapor lamp is superior to the concentrated-arc lamp in a number of respects, and it is probably capable of further improvement also, though primarily in mode of construction, shape, and size rather than in fundamental mode of operation. Its selective radiation characteristics and high efficiency of modulation approach the ideal realization of desirable characteristics for a specialized purpose about as closely as can be anticipated for any source. The development of flash lamps for certain special purposes has been highly successful; equally successful developments can undoubtedly be made in the future to meet other specialized requirements for this type of source.

At least one other type of source has been shown to possess interesting possibilities. Developed in France as the source for a near infrared communication system operating on a radio-frequency carrier wave, it consists of a pancake spiral discharge tube filled with xenon gas. The possibility of successfully applying it in a system of this type has been demonstrated [30] under Contract OEMsr-1391 by Northwestern University (see Chapter 4). It was subsequently purchased by the Navy (BuShips) for the further investigation and application which it apparently merits.[31]

It is very difficult to outline specific recommendations for the direction of future development of infrared sources. The line of attack will necessarily be affected by the military needs of the future, such as the size, weight, beam width, electrical characteristics, operating range, and security requirements, the degree of obsolescence of earlier systems through general knowledge, and the availability of components and their adoption by other countries, etc.

A considerable amount of interest has already been expressed in systems which would operate at a somewhat longer wavelength range than has heretofore been employed in the near infrared, namely from 1.5 to 3 or 3.5 μ. A source such as the incandescent tungsten lamp or the concentrated-arc lamp, whose radiations consist principally of a thermal continuum, emits an appreciable percentage of its energy in this region but is considerably less efficient here than for the region near one micron at which the peak spectral emission occurs for the operating temperatures near 3000 K which are ordinarily used to secure the highest feasible holobrightness. Decreasing the temperature of the source increases the percentage of the total energy radiated at the longer wavelengths, but at the expense of a lower energy emission per unit area, at each wavelength as well as integrated over all wavelengths. However, the radiant output in the desired wavelength region per watt input slowly increases as the temperature of the source is decreased from 3000 K to 2000 K or lower. Thus if the area of a source at the lower temperature can be increased in such a way that the same spatial distribution of signal flux as at the higher temperature is maintained, the operating range of a system will remain unchanged and its operating efficiency will be somewhat improved.

In the longer wavelength region the difficulties already encountered in electrically modulating such a source at the frequencies most useful for communication purposes will be multiplied still further. Although the Nernst glower radiates selectively near 2 μ, it is of the incandescent type and therefore cannot be modulated efficiently by direct electrical operation. The development of an electrically modulated lamp as efficient for this region as the cesium-vapor lamp is for the 0.9-μ region can scarcely be anticipated from the well-known spectral emission and other pertinent characteristics of the elements. It therefore appears likely that, for the immediate future, the only really feasible source for extending the application of modulated radiation appreciably farther into the infrared will emit a continuum from which the desired wavelength region will be selected by the use of filters developed for this purpose. With such a source it appears likely that any modulation desired at audio or higher frequencies must be superimposed on the radiation by mechanical means after it leaves the source, although these means may be subject to electrical control methods. The transmission characteristics of the atmosphere and of the envelopes in which the source and the detector are constructed will limit the wavelength region to which such developments may be extended with any degree of success. Other aspects of a possible development of this type are discussed in Chapter 4.

Chapter 2

NEAR INFRARED TRANSMITTING FILTERS

By *Richard C. Lord* [a]

2.1 INTRODUCTION

The present chapter is devoted to a discussion of near infrared transmitting filters used in military equipment developed under the auspices of Division 16, NDRC. Many of these filters were the outgrowth of investigations sponsored by Section 16.4 or Section 16.5, but some were the products of manufacturers who had no direct relation with NDRC in this connection. A minimum of background information on the general subject of infrared filters is included. Such information is widely available in scientific texts and journals and has been assembled in a comprehensive report.[1]

2.2 DEFINITION OF TERMS

The following terms are helpful in discussion of the properties and practical applications of infrared filters (see Appendix, Tables I and II).

Relative spectral responsivity, denoted r_λ, is the responsivity at any wavelength λ of a detector expressed in terms of an arbitrary scale in which the peak value of the responsivity is taken as unity. All other values are thus less than unity. This convention of setting the maximum value of a relative function equal to unity will be observed for the following quantities as well as for r_λ.

Relative luminosity, R_λ, is the relative spectral responsivity of the human eye.

Relative spectral radiant flux, ϕ_λ, is the flux in watts per micron at a particular wavelength λ of a radiant source for which the maximum value is 1 watt per micron.

The fractional transmission, T_λ, of radiation of wavelength λ by a filter is defined as the ratio of the total radiant flux of wavelength λ emergent from one face of the filter to the total radiant flux of the same wavelength incident on the other face of the filter. The path of the radiation in the filter may or may not be rectilinear. If the above definition is further restricted to radiant flux transmitted rectilinearly by the filter, the transmission so defined is called the *fractional specular transmission.* Clearly, the fractional specular transmission is smaller than the fractional transmission, and also the fractional transmission is no greater than unity.

With the help of the above concepts, the two quantities of fundamental importance in determining the performance of infrared filters in military devices may be defined. These two quantities are the *effective hololuminous transmission,* ehT, and *effective visual transmission,* evT. The former measures the efficacy of the filter in passing useful infrared radiation, and the latter the efficacy of the filter in blocking out unwanted visible radiation. In mathematical terms,

$$\mathrm{ehT} = \frac{\int_0^\infty \phi_\lambda T_\lambda r_\lambda d\lambda}{\int_0^\infty \phi_\lambda r_\lambda d\lambda}, \tag{1}$$

and

$$\mathrm{evT} = \frac{\int_0^\infty \phi_\lambda T_\lambda R_\lambda d\lambda}{\int_0^\infty \phi_\lambda R_\lambda d\lambda}. \tag{2}$$

The indicated integrations extend in principle from $\lambda = 0$ to $\lambda = \infty$. In practice, the λ range need not be greater than from $\lambda = 0.4\ \mu$ to $\lambda = 1.4\ \mu$, for the usual military sources and receivers, and frequently it is much smaller still.

It is clear from equations (1) and (2) that ehT and evT, that is to say, the performance characteristics of an infrared filter, do not depend on properties of the filter (T_λ) alone, but also on the infrared source-receiver combination with which the filter is used. The source and receiver must be stated or implied whenever ehT and evT values are given for an infrared filter. The convention has been adopted (see Appendix) of denoting by ehT° those ehT values obtained with a standard tungsten lamp operated at a color temperature of 2848 K. Actual or approximate relative spectral radiant flux functions (ϕ_λ) are given for several infrared sources in Chapter 1, Figure 14.[b] Similarly, in Chapter 3 the relative spectral responsivity r_λ of the various infrared-sensitive photocells is indicated.

[a] Massachusetts Institute of Technology.

[b] See also Summary Technical Report, Division 16, Volume 4, Chapter 5, Figures 7 and 29.

2.2.1 Determination of ehT

Irrespective of the nature of the military equipment concerned, if near infrared radiation is the basis of operation, the performance of the equipment is optimum if ehT is highest and evT lowest. Determination of these quantities is therefore prerequisite to a decision as to what filter is the best to use in a particular device.

Devices for the measurement of ehT have been described in NDRC and other reports.[2,3,4] These devices are essentially alike, consisting of a standard source of radiation, an optical system for collecting the radiation from the source and focusing it on the receiver, and the standard receiver itself. In addition, there is provision for insertion of a filter in the optical path at one place or another, depending on whether ehT or ehT (specular) is to be measured. The electrical output of the photocell receiver is amplified and measured in conventional fashion. Measurement of ehT is made by reading the output of the receiver when the source is emitting radiation with no infrared filter in the radiation path, and then reading the receiver output with the infrared filter placed in the optical path. The ratio of the latter reading to the former is the ehT of the filter for the particular source-receiver combination used, provided the readings obtained are linearly proportional to the radiation incident on the receiver. Clearly, ehT measured in this fashion must be numerically less than unity. Whether the value measured corresponds more closely to ehT or to ehT (specular) depends on the placement of the filter in the optical path. If the placement of the filter is made at a point where the radiation transmitted nonrectilinearly by the filter escapes from the optical path, ehT (specular) is determined, otherwise ehT.

It is possible to compute ehT for an infrared filter with respect to any source-receiver combination, when the numerical values of ϕ_λ, T_λ and r_λ are available at all pertinent wavelengths, by numerical integration according to equation (1). This procedure is somewhat laborious, although the results are reliable when the ϕ_λ, T_λ and r_λ values are fairly accurate. The method of finding T_λ, however, is just as difficult for one wavelength as is ehT for the entire range of wavelengths, so that the computation of ehT is of no advantage over direct measurement except in special situations. One such circumstance is that in which, for some reason, ϕ_λ or T_λ or r_λ is known, but the actual source or receiver or filter is not available for use in the determination of ehT.

Table 1 shows ehT values for various filters. All these values are for cesium-surface photocells, the source being incandescent tungsten at 2800 to 3000 K.

2.2.2 Determination of evT

The measurement of evT is attended by more difficulty than that of ehT. The primary reason for this is the fact that one desirable quality of an infrared filter is a minimum value of evT. Since this

TABLE 1. Values of ehT and evT for various near infrared filters.

Filter type	Base material	ehT range	evT range	Density
Corning 2540	Glass (2.6 mm)	0.13	10^{-7}	Medium high
Corning 2568	Glass (7.5 mm)	0.20	10^{-5}	Low
Polaroid XR3X	Cellophane, nylon	0.25–0.4	10^{-6} – 10^{-5}	Low
Polaroid XR7X	Cellophane, nylon	0.05–0.15	10^{-9} – 2×10^{-8}	High
Polaroid XRN1X	Polyvinyl alcohol	0.25–0.4	10^{-6} – 10^{-5}	Low
Polaroid XRN2X	Polyvinyl alcohol	0.07–0.17	10^{-10} – 10^{-8}	High
Polaroid XRN5X	Polyvinyl alcohol	0.3 –0.4	5×10^{-7} – 5×10^{-6}	Low
Ohio State Type I *	Melmac-Rezyl resin	0.5 –0.7	10^{-5} – 5×10^{-4}	Low
Ohio State Type II *	Melmac-Rezyl resin	0.4 –0.6	10^{-6} – 10^{-4}	Low
Ohio State Type III*	Melmac-Rezyl resin	0.2 –0.4	10^{-8} – 10^{-6}	Medium high
Ohio State Type IV *	Melmac-Rezyl resin	0.05–0.2	10^{-10} – 5×10^{-8}	High

* The type numbers I, II, III, IV have not been used by the Ohio State group but are used here for the sake of brevity. They refer serially to the four dyes for which data are summarized on page 19a of reference 12.

minimum value, for practical purposes, is seldom larger than 10^{-6}, whereas ehT is seldom as small as 10^{-2}, it is readily understandable that evT is harder to measure. Moreover, the calculation of evT is attended by equal difficulty because reasonably accurate values of T_λ, when T_λ is as small as 10^{-4}, and approximate values of T_λ, when T_λ is as small as 10^{-7}, are required.

There are two essentially different methods of measuring evT, a direct and an indirect method. The former makes use of a standard infrared filter whose evT is already known and involves a visual comparison, under controlled conditions, of the unknown with the standard filter. Various optical arrangements for this comparison, based on traditional techniques in visual photometry, have been used in Army, Navy, and NDRC laboratories in this country and by the Admiralty Research Laboratory in England. For example, the U. S. Naval Research Laboratory has modified the commercially available Macbeth illuminometer to enable evT's as small as 10^{-8} to be measured with good accuracy.[3a] Another arrangement which is similar to the above, but which enables simultaneous comparison of the unknown filter with two standards of any arbitrary difference in evT, is described in a report,[12a] and a British procedure for photometric measurement of evT is reported.[5]

The indirect method for finding evT consists of a measurement of the *normal visual range* [NVR], which is the visual range limit of a particular source viewed by the dark-adapted eye in total darkness. The NVR for a filter of unknown evT can be converted to evT with the help of the relationship

$$\text{evT} = \text{Constant}\ \frac{(\text{NVR})^2}{\text{cp}}. \qquad (3)$$

The value of the constant in the equation is best evaluated empirically for a particular observer or set of observers by measurement of NVR for a filter of known and similar evT used in conjunction with a source of known candlepower, cp.

Determination of evT in this fashion is beset with many sources of error. Some of these are described in a report[6] summarizing extensive studies on the visual range of various infrared sources carried out at Brown University (under Section 16.1). The reader is referred to this report for details on various methods of measurement of NVR itself, and the advantages and disadvantages of each. Despite the difficulty of getting consistent, reproducible, and accurate NVR values, use of this quantity is perhaps the most realistic way of evaluating evT for filters to be used for military purposes, especially for filters with very low evT ranges (evT $\leqq 10^{-9}$).

2.3 MILITARY REQUIREMENTS FOR INFRARED FILTERS

As the war progressed, it became apparent that the military requirements for infrared filters were of two different, and to some extent contradictory, sorts. Of great importance, of course, was the evT-ehT requirement, which may be termed the *spectral requirement.* In addition, however, physical ruggedness of filters was perhaps even more essential because of the severe treatment of all infrared equipment during field use. Under the heading of physical ruggedness one should include resistance to mechanical and thermal punishment of all kinds, as well as resistance to weathering, particularly to exposure to sunlight and salt spray. The physical endurance required of an infrared filter in a piece of military equipment varies greatly, of course, the demands being less on filters incorporated in intricate equipment such as an infrared phototelephone and more severe in a simple device such as a shipboard beacon. In general, however, it may be said that ruggedness is a requirement second to none regardless of the application involved. Moreover, it is agreed by those concerned with filter use for military purposes that there is still much room for improvement in the physical characteristics of filters.[4a]

Most of the NDRC-sponsored work on infrared filters was devoted to the development of filters of improved spectral characteristics. The spectral requirements for infrared filters for military use fall rather distinctly into two separate kinds, that for very low evT values, approaching 10^{-10}, and that for which higher evT values, 10^{-8} or even larger, are tolerable. We shall refer to these two types of filters as "high density" and "low density" respectively.

2.3.1 Requirements for High-Density Filters

From the fact that devices using near infrared radiation have an energy threshold below which they will not function, it is clear that such devices will function at longer ranges if more infrared radia-

tion is available. When this radiation is furnished by a filtered source, the higher the chT of the filter, the larger is the amount of infrared radiation obtainable from that particular source (Chapter 1). Consequently, all filters should have as high an chT as is consistent with other requirements, but these other requirements may demand a very low evT. Since high evT and high chT in general go together, high chT may have to be sacrificed if low evT is essential.

The military circumstances under which high-density filters are required may be described roughly as follows: If the military usefulness of an infrared device depends on the probability of visual detection of the device being as low as, say, 1 in 1,000, by enemy personnel at ranges of the order of 10 yards, a high-density filter is necessary. Of course, range of detection can be reduced by reducing the radiant flux of the source, but operating range is correspondingly reduced.

From equations (1) and (2) it can be seen that chT and evT depend not alone on T_λ, but on ϕ_λ, r_λ (for chT) and R_λ (for evT) as well. For incandescent filament sources, ϕ_λ is pretty well the same for one source as for another, so that an examination of r_λ and R_λ will be more indicative. The r_λ curves for cesium-surface photoelectric cells and for thallous sulfide photoconductive cells are shown in Figure 1, and R_λ, *plotted on a logarithmic scale,* in Figure 2.[c]

Comparison of Figures 1 and 2 shows that the human eye has residual sensitivity in the spectral region around 0.8 to 0.9 μ, where a considerable part of the useful sensitivity of the thallous sulfide and cesium photocells also lies. Hence a filter designed to absorb radiation in this region to reduce evT also reduces chT. The question therefore arises as to the best compromise to make.

It can be shown[1a] that the best high-density filters are not necessarily those with the steepest T_λ curves in the region between 0.8 and 0.9 μ. Rather, the important point is to achieve the necessary low evT by making sure that the steep part of the T_λ curve lies at sufficiently long wavelengths. This

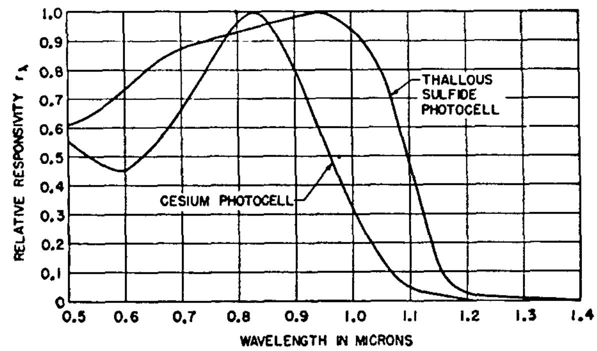


FIGURE 1. Relative responsivity for cesium and thallous sulfide photocells.

brings about some reduction in chT, to be sure, but the price must be paid if high-density filters are required. Examples of chT and evT for typical high-density filters for use with the Sniperscope[d] are listed in Table 1.

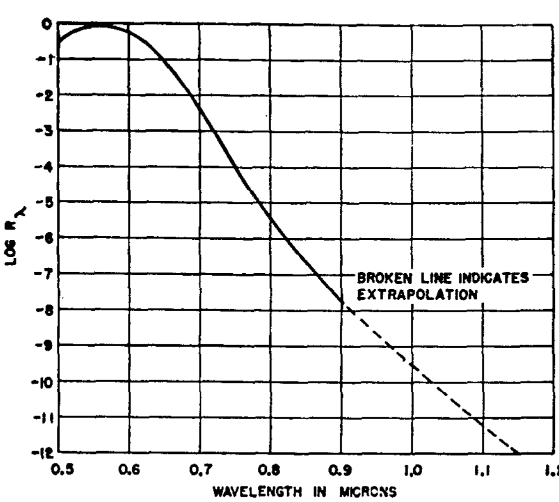


FIGURE 2. Logarithm of relative luminosity as a function of wavelength for cesium and thallous sulfide photocells.

The only cure for the deficiency in chT of high-density filters is to make use of near infrared detectors whose sensitivity curves have their maximum well beyond 1 μ (Chapter 3). With such detectors, it would be possible to make filters of indefinitely

[c] The R_λ curve is for photopic rather than scotopic vision. However, the slope of the photopic curve and that of the scotopic curve are very nearly equal throughout the extreme red from about 0.7 to 1.0 μ. Thus, evT's calculated from the two different curves for R_λ differ only by a constant factor so long as T_λ for the filter under consideration is essentially zero at wavelengths less than 0.7 μ (for military purposes, R_λ may be considered as zero at wavelengths longer than 1.0 μ). This constant factor is swallowed up in the empirical constant in equation (3) if evT's are determined by NVR measurement. If evT's are determined photometrically, the conditions of measurement decide whether they correspond to photopic or scotopic values. In the present volume, all evT values are based on the photopic curve.

[d] See Summary Technical Report, Division 16, Volume 4, Chapter 2.

low evT ($< 10^{-12}$) while maintaining relatively high ehT (say 0.5).

2.3.2 Requirements for Low-Density Filters

There are many military uses for infrared devices where much longer visual ranges for the infrared sources are tolerable, as, for example, with infrared communications systems aboard naval vessels (Chapter 4). Here the visual range may rise to several hundred yards or more without impairing the security of the device in operational use. Accordingly, an increase in ehT may be had to the extent allowed by whatever increase in evT is permissible. The percentage gain in ehT which results from a given percentage increase in evT is always many times smaller than the latter but may result in considerably increased operating range.

The precise requirements for low-density filters depend on the nature of the source-receiver combination. If the source is incandescent tungsten at about 3000 K and the receiver a thallous sulfide or cesium-surface photocell, a filter with a steep T_λ curve[e] located approximately at the right wavelengths for the evT requirements will give satisfactory ehT values. If the source is a special one, such as the cesium-vapor lamp, in which the spectral distribution of the radiation has two sharp maxima with a deep minimum between (Chapter 1, Table 7), the location of the steep portion of the T_λ curve may be quite critical for the ehT/evT ratio.

2.4 STATUS OF INFRARED FILTERS PRIOR TO 1941

There were several commercially available infrared filters in the prewar years, notably the glass filters of Jena and Corning (for example, Jena RG–7 and Corning No. 254) and the Wratten-dyed gelatin filters (Nos. 87 and 88a). These were designed for scientific and other nonmilitary uses and in general had shortcomings which made them unsuitable for military application. The glass filters could be made in sufficiently thick slabs to serve as high-density filters, but because of the comparatively gentle slope of their T_λ curves, the corresponding ehT values were undesirably small. In addition, the glass was thermally fragile. The dyed gelatin filters, on the other hand, were of too high evT even for low-density military uses, although the ehT was quite satisfactory. The unmounted gelatin film, of course, would be hopelessly delicate for military use, apart from its low heat resistance.

Thus it was apparent that research on near infrared filters should follow two main paths: (1) the development of physically rugged filters, and (2) the development of improved spectral characteristics, especially lower evT values and improved ehT/evT ratios.

Since glass was the most promising filter material from a mechanical standpoint, a program was undertaken by Corning Glass Works in this country and independently by Chance Brothers in England to increase the heat resistance of the glass used in infrared filters. In addition, study was made of the possibility of improving the T_λ curve for glass filters

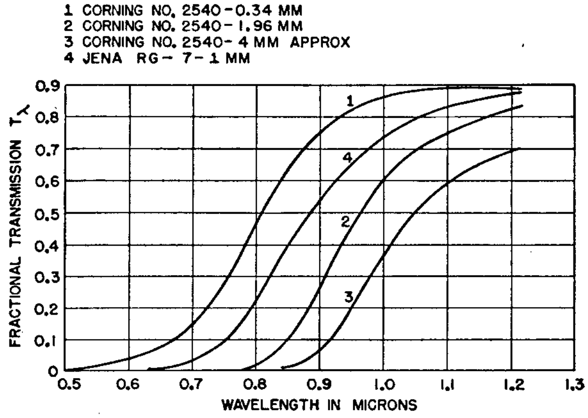


FIGURE 3. Transmission curves for several glass filters.

by use of new pigments or other means. The work done by Corning was on that firm's own initiative, although NDRC and Army and Navy laboratories were kept informed of progress and supplied with samples. The results of the work were disappointing, in so far as the T_λ curves are concerned. While glass infrared filters of vastly improved thermal properties were developed, the Corning 2560 series, the transmission curves of these glasses differed very little, when allowance is made for sample thickness, from that of the old No. 254 glass. A set of glass infrared filter transmission curves is shown in Figure 3.

[e] By "steep" curve is meant a T_λ curve such that $(1/T_\lambda)(dT_\lambda/d\lambda)$ is of the order of 50 reciprocal microns when T_λ is less than 0.5. Plastic filters approach or better this value, while glass filters usually have a value of around 10 to 20. It may be noted that $(1/R_\lambda)(dR_\lambda/d\lambda)$ has a value of -70 reciprocal microns at 0.8 μ.

2.5 INFRARED FILTERS DEVELOPED BY NDRC (1942-45)

The infrared filter developments sponsored by Division 16 of NDRC had as their object the investigation of the use of organic dyes in various media. Dyes have much steeper transmission curves than those of the pigments used in glass infrared filters, and, in addition, the location of the transmission curve on the wavelength scale can be determined almost at will by proper selection of the dye.

The organic dye has to be incorporated in some base, of course, and since the physical properties of the filter are no better than those of the base, the development of a good base is as important as finding a good dye. In fact, experience has shown it to be more important. The number of optically satisfactory materials in which organic dyes can be put is considerable but not infinite, and is limited essentially to plastics, whether natural or synthetic. Of the two NDRC-sponsored projects on infrared filters, one was concerned essentially with the study of various plastic materials which can be dyed in the form of thin sheets, while the other investigated plastics in which the dye could be incorporated in the monomeric form prior to the polymerization process. The results of these two projects will be summarized briefly.

2.5.1 Polaroid Filter Investigation[13]

Because of its experience with the commercial production of optical filters of various kinds, the Polaroid Corporation was asked to conduct a program for the development of improved dyed plastic filters. Prior to the beginning of this program, Polaroid had on its own initiative developed and put into pilot production its XRX type of filter. This type consisted of cellophane sheet vat-dyed with appropriate dyes to give either low-density or high-density filters. The former were denoted XR3X and the latter XR5X and XR7X. The proper density within each type could be obtained by adjustment of the dyeing time, longer time in the dyeing vats giving higher densities. Most of these filters were made with two dyes, a red and a blue, in order to provide the necessary high density throughout the wavelength region from 0.4 to 0.8 μ.

The transmission curves of several cellophane XRX filters are shown in Figure 4, and ehT and evT values are given in Table 1. It can be seen that both for high-density and low-density types the ehT and evT are quite satisfactory.

The fabrication of a finished filter from the dyed cellophane sheet consisted of bonding the sheet to a glass support of the desired size and shape. The sheet could be applied without difficulty to glass flats of various shapes, to cylinders, and even to hemispheres. Since the bonding material was usually polyvinyl alcohol, which is pervious to water, the filter was coated with a waterproof varnish.

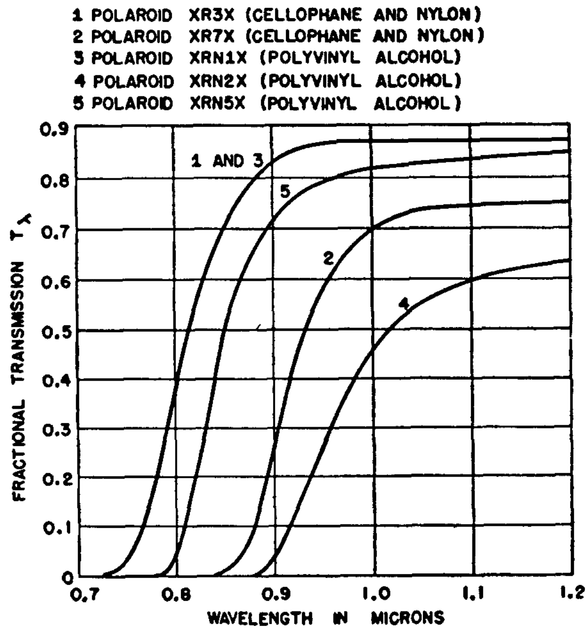


FIGURE 4. Transmission curves for several XRX filters.

Heat Resistance

The chief shortcoming of the glass-supported cellophane filter is its poor heat resistance. This difficulty is associated with the cellophane base itself and not with the vat dyes, which are stable at much higher temperatures than the cellophane. In fact while the dyes themselves will remain stable at temperatures of 200 C or higher for many hours, cellophane becomes brittle and cracks after relatively short exposure (several hours) to temperatures around 120 to 130 C. In addition, cellophane filters in field operation and in severe weathering tests showed tendencies toward formation of pinholes and cracks.

Accordingly the Polaroid contract had as its first objective the finding, if possible, of an optically

clear plastic sheet which would accept dye as satisfactorily as cellophane but would be much more heat- and weather-resistant.

Nylon Filters

After investigating a number of plastic bases, Polaroid found that nylon film, duPont type 6A, which has much better heat stability than cellophane, could be dyed satisfactorily with the same dyes used in the XRX filters. Curves of T_λ for typical dyed nylon sheet filters are shown in Figure 4, and approximate ehT and evT values are given in Table 1.

The dyed nylon sheet was bonded to glass supports in appropriate shapes for various military applications. The bonding technique was unusual because of the special character of nylon. A phenol-formaldehyde cement, Chrysler Cycle-Weld 55–6, was the bonding agent, and the bonding process was carried out under pressure (4 to 5 atmospheres) and at elevated temperatures (about 150 C).

Extensive testing of the nylon XRX type of filter indicates that from an optical point of view its qualities are quite satisfactory. There is no doubt that nylon filters are much more stable to heat, and particularly to alternate heat and cold, than are cellophane filters. The weathering properties of nylon filters are also much superior to those of cellophane. However, in both respects nylon filters still leave much to be desired. In particular, the heat resistance of the nylon base is still inferior to that of the filter dyes. Accordingly, vat-dyed filters of still better heat stability are possible, even with present dyes.

Evaporated Filters

The fact that the vat dyes are more heat-stable than their plastic bases led to an interesting filter development which may have possibilities, even though, for practical reasons, these were not exploited during the lifetime of Contract OEMsr–1085. Polaroid found that the dyes could be evaporated in vacuo and deposited in thin films on a supporting base in the manner employed in the evaporation of metals. Numerous filters of excellent spectral properties and highly improved heat stability were made in this fashion. The project was abandoned because of difficulties with quantity production of evaporated filters. It is conceivable, however, that these difficulties could be overcome and that evaporated filters might be a practicable answer to the quest for heat-stable dye filters.

PVA Filters

While work was in progress on filters of improved heat and weather stability, a special need arose for low-density filters of favorable ehT to evT ratio. These filters were to be used with low temperature sources, the cesium-vapor lamp and the type D–2 beacon (see Chapter 1), in such a way that neither the heat stability nor weathering properties were of paramount importance. Accordingly, it was possible to concentrate attention on the spectral properties of the filter.

The success of the British in making excellent low-density filters with a *polyvinyl alcohol* [PVA] base suggested this plastic for trial. It was soon found that cast PVA sheet, in which the dye had been incorporated before casting, gave filters of the best optical quality yet obtained. The problem of producing a satisfactory filter thus was reduced to that of finding the best PVA-soluble dye for the purpose and the best way of mounting the PVA sheet.

Several hundred dyes were studied in the development of the PVA series (denoted XRNX), the best of which are described in a report.[13a] T_λ curves as well as ehT and evT values for several typical XRNX filters are given in Figure 4 and Table 1. Field trials with equipment using the cesium-vapor lamp as a source (e.g., type E equipment described in Section 4.4.2) showed that properly selected PVA filters gave very high efficiency, as judged by the ratio of operating range to visual range.

Because PVA sheet is vulnerable to moisture, it is best mounted on glass in a sandwich type of lamination. The PVA lends itself well to standard laminating procedures, but it is necessary to pay special attention to the edge-sealing of the sandwich. Another important point is the kind of glass used in the sandwich. Many commercial glasses with a greenish tinge show pronounced absorption at around 0.9 μ. Such glass can reduce the ehT of the sandwich by 10 per cent or more and should not be used. It is easy to obtain satisfactory glass, provided one remembers to check the T_λ of the glass in the 0.8- to 1.2-μ region.

Other Polaroid Research

The remainder of the Polaroid program was devoted to the development of filters suitable for

sources and receivers operating at wavelengths longer than 1.4 μ. This work was begun toward the end of the program and will be discussed briefly in Section 2.7.

2.5.2 Ohio State Research Foundation Filter Investigation [12]

The second of the two NDRC-sponsored infrared filter projects was initiated originally for a somewhat different purpose from that of the Polaroid project. In mid-1943, it appeared that enemy use of the near infrared, as defined by the cesium-surfaced photocell, made imperative an extension of our infrared devices, both image-forming and non-image-forming, into the wavelength region beyond 1.4 μ. One promising approach lay through the development of infrared-sensitive phosphors, and a large program was initiated with this objective.[f]

FILTERS FOR RADIATION BEYOND 1.4 MICRONS

In order to utilize radiation in the region beyond 1.4 μ, without at the same time violating security from an enemy equipped with cesium-surfaced detecting equipment, infrared filters are needed which will transmit freely radiation at 1.4 μ and longer, and strongly absorb shorter wavelengths. The group in the Laboratory of Chemical Spectroscopy at Ohio State University was asked to develop such filters. This group was already participating in the phosphor program as a testing laboratory, and was familiar with the scientific and military background of the proposed filter investigation. The Ohio State University Contract OEMsr-987 was set up and administered by Section 16.5, but its filter developments are reported here rather than in Volume 4 for the sake of a unified discussion of filters. In actual practice, the Ohio State filters were developed for, and used in conjunction with, non-image-forming devices of Section 16.4 as well as for the image-forming devices described in Volume 4.

The first approach to the problem of making a filter with vanishingly small transmission at 1 μ was to examine the absorption spectra of various substances, both organic and inorganic, in this region. It appeared that copper salts in solution have satisfactory absorption characteristics. After much experimentation, a filter consisting of 30 per cent copper oleate dissolved in oleic acid was developed. At the elevated temperatures of operational use, the filter medium was liquid, so that the filter consisted of a liquid-tight cell with sylphon bellows as an integral part of the cell. The bellows expanded with temperature-dilation of the liquid. The T_λ curve for a typical copper oleate filter is shown in Figure 5.

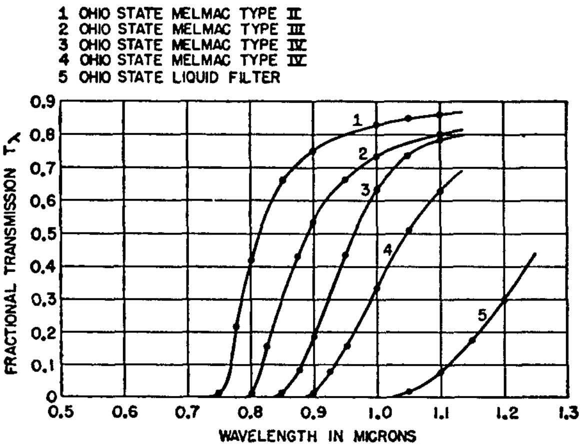


FIGURE 5. Infrared transmission curves for Melmac and liquid filters.

FILTERS FOR SHORTER WAVELENGTHS

The objectives of the Ohio State project changed as a result of two occurrences. The first was the failure of the phosphor program to produce a phosphor with adequate sensitivity at wavelengths beyond 1.2 μ, so that a need for longer wavelength filters did not materialize. The second was the increased demand for improved infrared filters at the shorter wavelengths. In the early part of 1944, therefore, the project began the study of plastic media suitable for filters and of infrared-transparent organic dyes which could be incorporated in these media.

The Melmac Plastic Filter. A considerable program of study of plastics was undertaken. As has been indicated in earlier discussion, the primary consideration in the choice of a plastic base is physical ruggedness, heat, and weather resistance in particular. The Ohio State group, after testing numerous plastics, reached the conclusion that a commercial melamine resin known as Melmac 599-8, when combined with the proper proportions (approximately 1 to 1) of an alkyd resin Rezyl 330-5, showed the best overall properties. The Melmac plastic has good heat resistance at 150 C, excellent weather stability and satisfactory mechanical prop-

[f] See Summary Technical Report of Division 16, Volume 4.

erties. It takes appropriate dyes and the optical properties of the dyed plastic are excellent.

The best feature of the Melmac plastic is the excellent bond it forms to a clean glass surface. This bond serves as the basis for fabrication of filters from the resin. In the fabrication of flat filters, such as the coated flashlight disks furnished by the Ohio State group to the Signal Corps,[11] the resin with the incorporated dye is poured in proper amount upon the carefully leveled surface of the disk to be coated. The film is allowed to dry in air for several hours, and is then polymerized by baking at a temperature of 100 C for a like period or longer. The resultant resin-to-glass bond is so strong that the glass or plastic will fracture before the bond.

An additional useful feature of the Melmac resin filter material is that dilution of the dyed resin with 20 to 30 per cent butyl Cellosolve makes it suitable for spraying in conventional fashion. In this way complicated nonplanar surfaces can be coated. It is difficult, of course, to secure uniform filter thickness in a sprayed coat, but the same difficulty is encountered whenever complicated filters are fabricated from glass or molded plastic.

FILTER RESEARCH AND PRODUCTION

The Ohio State group carried out a survey of suitable organic dyes similar to that made by the Polaroid Corporation and described above. The two surveys were not duplication of effort, since the Polaroid search was for water-soluble and the Ohio State search for spirit-soluble dyes. A list of dyes found to be satisfactory is given in a report,[12b] and T_λ curves for filters made with some of these are given in Figure 5. Values of ehT and evT are given in Table 1.

In addition to its research program, the Ohio State group did a considerable amount of actual production of its filters, and also aided the Armed Services in the establishment of production at other locations. The work of the group will be continued under the sponsorship of the U. S. Army Corps of Engineers.

2.6 USE OF FILTERS IN MILITARY DEVICES

It is not necessary to discuss here the specific applications of the filters just described to military instruments, inasmuch as this subject is considered in detail in other parts of this volume and in Volume 4. The use of filters with various sources, receivers, signaling and communications systems, as well as with beacons, markers, and other infrared devices is adequately described in contractors' reports concerning the development of these devices, and also in other parts of the Summary Technical Report.

2.7 FUTURE DEVELOPMENTS IN MILITARY INFRARED FILTERS

2.7.1 Near Infrared Filters

Ample room remains for the improvement of near infrared filters. The filters of best mechanical properties (glass) have poorest spectral qualities, and there appears to be no intrinsic reason why glass pigments cannot be found which give much improved transmission curves. Certainly one may expect considerable improvement in plastic filters to result from the discovery of new plastics, or the exploitation of old plastics not hitherto used. There is reason to doubt, however, whether any considerable research effort directed toward this improvement would be justified. The future of military infrared appears to lie in wavelength regions well beyond 1 μ, where the eye has no usable sensitivity, so that no compromise between ehT and evT is necessary.

2.7.2 Intermediate Infrared Filters

The possibility of discovering infrared phosphors sensitive to wavelengths above 1.4 μ prompted the first investigation of longer wavelength filters. Later, when we learned that the Germans had developed the lead sulfide detector, whose sensitivity prevails out beyond 3 μ, the need for intermediate infrared filters became apparent. Toward the end of the war, the Polaroid group was asked to consider the development of infrared filters transmitting less than 1 per cent at 1.4 μ and as much as possible at longer wavelengths. Four types of filters were investigated, no one of which was completely studied. These were metallic sulfide layer filters; furan plastic filters; green glass XRNX filters; and sulfur-dyed PVA filters. All of these show considerable promise and should be studied further for ehT values with respect to lead sulfide cells. In addition other possibilities such as interference layer filters should be explored.

If image-forming devices using lead sulfide or other materials sensitive in the intermediate infrared are developed, it appears likely that they will supersede the shorter wavelength devices. In such an event, a vigorous research program on intermediate infrared filters is a necessity.

2.7.3 Far Infrared Filters

It is beyond the scope of this chapter to discuss infrared filters for the 10-μ region, on which some work was done during the war. Since these filters were not primarily security devices but were for the improvement of the sensitivity of heat detectors, their efficiency did not have to be great. If image-forming devices for the 10-μ region are developed or if strong, modulable sources of 10-μ radiation can be made, the status of the far infrared region will resemble that of the intermediate infrared. At the present time this prospect seems rather distant, and the need for research on far infrared filters is not pressing.

2.8 SUMMARY

The near infrared filters available commercially at the end of 1941 were not suitable for use in most of the military infrared devices then and later developed by NDRC contractors. Accordingly, an NDRC-sponsored program of improvement in filters was initiated. The objectives of the program were to obtain filters of better spectral quality and of greatly increased ruggedness. Two projects were set up, one at the Polaroid Corporation, sponsored by Section 16.4, NDRC, and one at Ohio State University, sponsored by Section 16.5.

The Polaroid project developed vat-dyed plastic sheet filters using cellophane, nylon, and polyvinyl alcohol sheet. The dyed sheet was supported by bonding it to glass. These filters had excellent spectral quality and a wide range of densities, but their low heat stability did not permit their use with high-powered sources.

The Ohio State project developed a dyed lacquer filter with a melamine resin base. The dyes which could be incorporated in this base gave the resultant filters excellent spectral quality, and the physical characteristics of the resin were also quite good. However, it, too, was unstable at high temperatures and could not be used with high-powered sources.

Much room for improvement in the heat resistance of near infrared filters still exists. Whether the necessary research effort is worth expending, however, is dependent upon future developments in the fields of intermediate (1.5 to 5 μ) and far (5 to 15 μ) infrared. In particular, if intermediate infrared sources and detecting devices are developed with performances comparable to those of the devices now available in the near infrared, extensive work in the field of intermediate infrared filters will be called for.

Chapter 3

NON-IMAGE-FORMING NEAR INFRARED DETECTING DEVICES

By *John R. Platt* [a]

3.1 INTRODUCTION

3.1.1 Object and Scope of Chapter

THIS CHAPTER is concerned with developments, primarily those sponsored by NDRC, in the field of *near infrared* [NIR] detecting devices. These are devices which give a signal in response to the total amount of NIR radiation falling on them, regardless of the direction of incidence and distribution pattern of the radiation or whether it is brought to a precise focus.[b]

The devices discussed here produce an electrical signal when flux of radiation falls on them. They are of three kinds, namely, photoemissive, photovoltaic, and photoconductive.

The photoemissive type is represented by vacuum and gas-filled phototubes and photomultipliers. In these, the main effect of the radiation can be regarded as the production of an electric current in a device with an input impedance of hundreds or thousands of megohms. Phototubes with cathodes sensitive to NIR radiation have been commercially available for many years, and no further developments in this field were undertaken by NDRC. While some photomultipliers sensitive to NIR radiation have been manufactured commercially, they were not commonly available before the war. Consequently, work was undertaken under NDRC auspices to develop NIR photomultipliers with improved response characteristics and in the sizes and designs needed for specific equipments being developed for military purposes.

Comparative studies of phototubes were made by various NDRC groups in the course of other work; some are mentioned in Section 3.2.

The photovoltaic, photoemf, or barrier-layer cell is also in common use in light meters, footcandle meters, etc. In such a cell, the main effect of radiation is the production of a small voltage in a low-resistance device. This effect is ill suited for electronic amplification, unless the excellent thermocouple circuits developed under NDRC during the war (see Chapter 8) could be applied to the problem. No NIR photovoltaic development was undertaken very seriously by NDRC, although some unstable photoemf cells were produced in the course of the work described in Section 3.3.1.

The great NDRC emphasis was on the third kind of cell, namely, the photoconductive, with six contracts eventually devoted to the study and development of manufacturing techniques for such cells, as described in Section 3.3. In addition many other contracts applied them as detectors in communication and signaling systems (Chapters 4 and 5) and heat-detection systems (Chapter 9). No photoconductive cells were commercially available when this work was started, but more than ten thousand of them were produced in consequence of the work described here. In these cells the principal effect of radiation may be described as a change of resistance which is associated with a change of potential difference or current if a current has been flowing previously. They can be made with resistances of the order of 10 megohms, large enough to work well with amplifiers but small enough so that they are not as much affected by humidity and surface leakages as the much higher resistance phototubes.

The two most successful photoconductive types made were the Cashman-type thallous sulfide [TF] cells, responsive in the NIR from the visible region out to wavelengths of 1.4 μ (Section 3.3.1), and the lead sulfide [PbS] cells, responsive in the NIR and beyond in the *intermediate infrared* [IIR] out to 3.6 μ (Section 3.3.2). The TF cell has a responsivity in the NIR equal to or better than that of the best NIR-sensitive phototubes. Its relative infrared response, as measured by the *standard effective holotransmission*, ehT° (see Chapter 2 and Appendix), of common NIR-transmitting filters, with respect to a standard tungsten source at 2848 K color temperature, is much higher than that of the available phototubes.

The PbS cell is not so responsive unless it is

[a] Northwestern University, Evanston, Ill. Now at the University of Chicago, Chicago, Ill.

[b] Image-forming NIR receivers, such as metascopes, electron telescopes, and dissector tubes developed under NDRC, are treated in the Summary Technical Report, Division 16, Volume 4.

cooled to solid CO_2 temperatures or below, but its long wavelength threshold makes it an excellent and promising detector of thermal radiators whose temperature is only a few degrees above that of their background. In one preliminary test[11] a dry-ice-cooled PbS-cell system was found to detect thermal radiation in the IIR from a ship at up to half the range obtained with the intensively developed *far infrared* [FIR] bolometer detectors (Chapter 8). The speed of response of the PbS cell is much greater than that of the bolometers. For a given amount of energy in its most sensitive region, below about 3 μ, the PbS cell is of the order of 100 times more sensitive than thermal detectors, and it will have many scientific uses in this wavelength range.

A number of theoretical problems have been raised by the TF and PbS cells, as discussed in Section 3.3.1. Much of the theory developed is applicable to photodetectors generally, such as the discussion of signal, noise, frequency, area, background light, etc., but it is presented with the TF-cell discussion in Section 3.3.1 because it was of the greatest interest in its application to this cell. Some techniques of test and measurement presented there have a wider application, too.

Both silicon and selenium photoconductive cells were also the subject of studies by NDRC (see Sections 3.3.3 and 3.3.4), but did not yield such fruitful practical results.

3.1.2 Military Applications of NIR and IIR Detectors

The detectors described here may be used in at least three different kinds of military devices: infrared communication and signaling systems, infrared radar systems, and heat-detecting devices.

Any NIR or IIR detector can be used in a signaling system to indicate the flashing of some beacon which is covered with a suitable filter to give visual security. Detection of *modulated* light, however, requires short response times. With the exception of the selenium cell, the detectors described here have response times short enough to detect modulated NIR radiation up to 2,000 cycles (Chapters 4 and 5). They consequently are excellent detectors for voice or code communication.

This kind of infrared signaling or communication has the military advantage that it can be secret and horizon-limited. It can come from a narrow-angle source so filtered that it is detectable only by other NIR or IIR detectors of exactly the right kind pointed in exactly the right direction (Section 4.1.2). These detectors therefore make available for military use two new, secure communication channels, the NIR and the IIR (see Section 4.8), which can be used under combat conditions requiring radio and radar silence.

For infrared radar systems, where the cells are used for detecting NIR reflections from mirrors or diffuse targets, cells with very short response times, a few microseconds or less, are required. Such response times are obtained only with vacuum phototubes and multipliers. The multipliers discussed here were used in an *infrared radar* [IRRAD] system described in Chapter 6.

For thermal detection the requirement on cells is a long wavelength threshold in the IIR. Such thresholds are possessed only by the PbS cell and some related cells as yet little developed. These cells may be used to locate and track warm military objects such as men, guns, tanks, ships, planes, motor exhausts, etc. A comparison of PbS cells with bolometers was given above. Evidently the PbS-cell sensitivity to the radiation from the target is comparable with that of bolometers and may become better with further development, even though only a small fraction of the total radiation emitted by the target can be utilized by the PbS cell because of the limited region of spectral response (Section 4.8). The speed of response of the PbS cell compared to bolometers may be a great military asset.

All of these detector functions have been utilized in World War II. German, Italian, and Japanese voice infrared communication systems saw field use; British, French, and American systems were developed and at least put into production (Chapter 4). The Germans used PbS cells for detecting ship targets at night in the English Channel and in experimental proximity fuzes.

It seems likely that the NIR-IIR communication function will grow in military interest, and that the combined heat-detection, homing-bomb, guiding, and tracker problems may rise to supreme importance.

3.2 PHOTOTUBES AND PHOTOMULTIPLIERS

Almost all of the NDRC work on NIR-sensitive photoemissive cells was carried out under Farns-

worth Television and Radio Corporation Contract OEMsr–1094. This contract was principally devoted to the manufacture of special multipliers, but a few special infrared-sensitive vacuum and gas-filled phototubes needed by other NDRC contracts were also constructed under this contract as a matter of expedience.

Special NDRC development programs on vacuum and gas-filled infrared-sensitive phototubes were not undertaken, because it was felt that these were already well developed commercially and were widely available with enough different sizes and characteristics (see any RCA Tube Handbook, for example) to fulfill almost any foreseeable military need.

With infrared-sensitive multipliers, the case was different. The cesium and silver oxide (type S_1) surfaces needed to produce high-infrared responsivity seem to be more difficult to manufacture than blue-sensitive surfaces. The few commercial NIR multiplier types which had been previously in production, by Western Electric Company, Farnsworth, and RCA, had been discontinued by the time the war started. The contract with Farnsworth for multipliers was consequently initiated in June 1943, so that fast-response-time NIR detectors could be obtained which would be suitable for both audio-frequency and radio-frequency NIR communication systems (Chapter 4), for infrared radar (Chapter 6), etc.

Although no other NIR phototube development was undertaken by NDRC, extensive comparative measurements of many tubes and photoconductive cells were made by University of Michigan Contract NDCrc–185 and by Northwestern University Contract OEMsr–990. In addition some phototube circuit developments of especial value for voice communication reception were achieved by the latter contract, as reported in Section 4.4.2.[30] Both contracts, together with Northwestern University Contract OEMsr-235, also investigated enemy phototube characteristics, as mentioned in Section 4.3.

Additional studies of the operating characteristics of the Farnsworth multipliers were made by Western Electric Company Contract NDCrc–185 in connection with the IRRAD work and are reported in Chapter 6.

Some other work on photoemissive devices deserves brief mention at this point. This was the study of NIR photoemission from alkali blacks by Johns Hopkins University Contract OEMsr–610 in 1943–44, under Project Control AC–63, as a side line from some other work they had been doing.

By evaporating the metals at low air pressure rather than in vacuum, it was found that sodium, potassium, cadmium, and tellurium "blacks" (oxides) might be deposited on a glass plate. These surfaces had considerably longer wavelength thresholds than the pure metal evaporated in vacuum, 9500 A for sodium black, for example, as compared with 5900 A for metallic sodium. No permanently sensitive cells were prepared, and the most promising cell, formed by a deposit of tellurium black with a maximum spectral response near 1.6 μ, was less sensitive than an old Case Thalofide cell (Section 3.3.3) by a factor of about 200. The study was therefore not continued.

Course of Development

Farnsworth Contract OEMsr–1094 was initiated in June 1943 to study the general optical and electrical characteristics of photomultiplier tubes and to develop and construct such tubes for specific purposes, emphasizing wide angle of view, good infrared responsivity, and high signal-to-noise ratio.[21,22,31]

The contract started under Project Control NS–159, concerned with ship-to-ship communication. Later NR–103 and CE–22, concerned with IRRAD, were applied when it appeared that those executing the original contract would be devoting most of their time to the development of special photomultipliers for IRRAD.

In the course of the work the contract built some 130 6-stage (6PE series) end-view multipliers, mainly for use by various NIR communication contracts and for NIR laboratory photometry; about 70 14-stage tubes (14PE series), 6 11-stage tubes (11PE series), and 90 10-stage tubes, for use in IRRAD systems; and some 70 vacuum and gas-filled NIR phototubes of special design which were made for various other contracts for communication studies and other purposes.

The experimental work of the contract was terminated in August 1945.

Details of Construction and Performance

Some general characteristics of multipliers may be brought to mind. The signal response is inde-

pendent of frequency up into the megacycle region. Noise is largely "shot noise" and noise from leakage currents, and has a white spectrum independent of frequency for constant bandwidth. It is well known that for such a spectrum the rms noise is proportional to the square root of the bandwidth. These characteristics are quite different from those of the photoconductive cells to be discussed later.

All of the tubes made had cesium-silver-oxide type S_1 cathode surfaces. A typical spectral-response curve for such a surface is shown in Figure 7. The curves are very variable, as the cleaning, oxidation, and silvering of the cesium surfaces, which are the processes important in obtaining high infrared response, cannot be carried out reproducibly. Relative NIR response on each Farnsworth tube was determined from the ehT° of a Polaroid Corporation XR3X48 infrared-transmitting filter (see Chapter 2) with respect to the tube in question. The ehT° values obtained range from 5 to 40 per cent, median about 20 per cent. The values seem to be related to the absolute responsivity of the tubes or to any other parameter of cell construction.

In the 1944 work, the cesium for the surfaces was introduced into the tubes by distillation from glass capsules which were opened when the tube was being formed. Later, in the 6-stage tubes, the cesium was developed from pellets containing cesium chromate and a reducer. These were placed in a side tube which could be heated or cooled to regulate the amount of cesium.

The thermionic current from the surface being formed was measured during evaporation to indicate when the layer had reached the correct thickness. An attempt was made to govern the thickness by evaporating until maximum infrared sensitivity was obtained, but tubes so formed were invariably very noisy, so the thermionic indication was used instead.

Six-Stage End-View Multipliers. The 6-stage tubes were similar to that shown in Figure 1, except for variations in bulb shape and socket design. The tubes had a dish-shaped cathode, six multiplying boxes, each about $\frac{3}{16}$x$\frac{3}{16}$x$\frac{1}{4}$ inch in size, and a collector plate. The usual cathode diameter was $\frac{7}{8}$ inch, the external tube diameter $1\frac{3}{8}$ to $1\frac{1}{2}$ inches, and the tube length 3 or 4 inches. The overall voltage could be from 1,500 to 3,000 volts, depending on the tube. About 0.1 watt could be safely dissipated in the collector.

Out of 64 6PEA tubes built, 36 were considered usable. The responsivities of these varied from 40 to 440 ma per hololumen.

The response was not very uniform across the cathode surface, because of the poor electron focusing which resulted from designs having the first multiplier stage at one edge of a large cathode. Noise was not measured.

On these first tubes, the end window was made flat in order to give a wide angle of view, but the window apparently accumulated charges which reduced the response at low light levels.

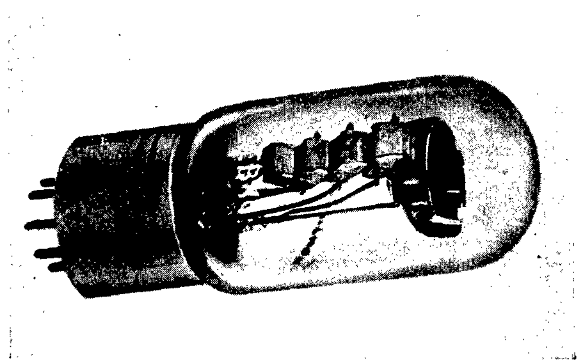


FIGURE 1. Six-stage multiplier.

The *signal-to-noise* ratio [S/N] was improved by using a hemispherical window in Type 6PEB. About 30 tubes out of 50 of this type were usable, with responsivities from 30 to 1,500 ma per hololumen. The signal equivalent of noise varied from below 5×10^{-9} up to 10^{-7} hlm, reduced to a 25-cycle bandwidth.

Twelve 6PEC tubes were made with a new base. Six were usable. Responsivity was 70 to 500 ma per hololumen, and the noise equivalent was between 2×10^{-8} and 10^{-7} hlm at 25-cycle width.

Fourteen-Stage Tubes. Several 14-stage multipliers, to fit into a $2\frac{1}{2}$-inch shell, were built for the triple-mirror form of IRRAD (Chapter 6) developed by Western Electric under Contract OEMsr-1267. A high multiplication factor and a high output current were wanted so as to reduce the need for thermionic amplification.

These requirements necessitated larger multiplying stages than had been used previously, the omission of the side walls on these stages, and a construction in which all the leads are carried directly through the glass walls by individual seals.

The type finally arrived at is 7 inches long and

1⅝ inches in diameter, with a cathode area of ⅜x1 inch, and with all stages 1 inch long. Thirty-two tubes of the final type were made of which 14 were usable. Overall voltages were 1,700 to 2,500, responsivity 10 to 200 amp per hololumen; the noise equivalent was 3×10^{-10} to 2×10^{-8} hlm at 25-cycle bandwidth.

This final type, 14PEI, was arrived at only after construction of some 35 intermediate and experimental types to find the best design. In the first tubes built the current output choked up (saturated) at voltages as low as 900 volts in some cases, and was not increased by raising the voltage. This situation was improved by omitting side walls on the later stages and making them larger. Still more improvement was obtained by bringing the leads out of the side of the tube (see Figure 3), as it was found that they had been distorting the dynode fields when they were taken out at the base. Another solution, found successful on one experimental tube, is to leave the leads inside the tube, bringing them out of the base as usual but enclosing them inside the tube in individual glass sheaths.

Eleven-Stage Multipliers. These tubes were constructed for use in the diffuse-reflecting IRRAD equipment assembled by the University of Michigan under Contract NDCrc–185. The final tube, 11PEJ, is 2⅛ inches in diameter and 8 inches long, with ⅝x1⅝-inch cathode area. All stages are 1⅝ inches long. The leads are brought out the side.

Six tubes were made, 4 usable. Operating voltages were from 2,000 to 2,400; responsivity, 3 to 70 amp per hololumen; noise, 10^{-9} to 5×10^{-8} for 25 cycles.

Ten-Stage Multipliers. For a modified IRRAD system being developed by Bell Telephone Laboratories under Contract OEMsr–1267 for Navy use, a 10-stage tube was worked out which was designed to feed into a thermionic amplifier. It was to have a full-cone angle of acceptance of 80 degrees and cathode area 0.3x0.5 inches. Some 90 tubes of various designs were constructed in attempting to meet these requirements and the stringent restrictions on overall size and weight, but few of the tubes were very good and the final design was not yet fixed at the termination of the contract.

The first type made was a modification of the successful 14-stage type, but inconvenient restrictions were placed on tube diameter and lead location by the mechanical requirements, and no tubes were satisfactory. Another type had a translucent cathode, which permits an easy fulfillment of the optical requirements, but the one tube made turned out to be poor.

A number of side-view tubes were made. Special techniques for making glass molds for lead-ins were worked out so as to reduce fluorescence, which had been found to increase the noise level. Metal, glass, and mica screens were tried between stages, and sharp points on lead wires were eliminated in an attempt to avoid corona discharge. Stages were made with and without side walls. New cathode shapes were developed to improve the electrostatic collection of the primary electrons.

It was believed at the end of the contract that most of the problems of this 10-stage system had been solved and that a final design could then have been quickly evolved and produced on a large scale if desired. Some 12 tubes out of the 90 built during this study were regarded as fairly satisfactory. Optimum voltages on these ranged from 1,400 to 3,200; the sensitivity was from 0.4 to 6 amp per hololumen; and the noise equivalent was from 3×10^{-9} to 10^{-7} hlm for 25 cycles.

Special Tubes. A number of special multiplier tubes were made and designs for others were worked out under Contract OEMsr–1094. Among these were tubes with the first stage operating through a hole in the center of the cathode, which gave more uniform sensitivity over the cathode surface than with

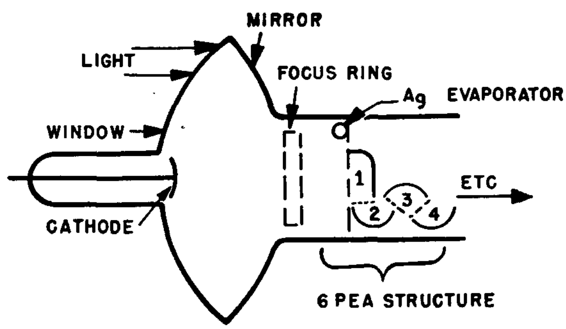


FIGURE 2. Built-in reflection-optical system.

the first stage at the side as in the usual design. Other tubes were designed like that shown in Figure 2, with a built-in reflection-optical system. A 14-stage multiplier having grid or mesh stages was designed; this form is very economical of space, since the electrons travel straight down the tubes without complicated focusing structures and paths. The 30-stage tube shown in Figure 3 was built for

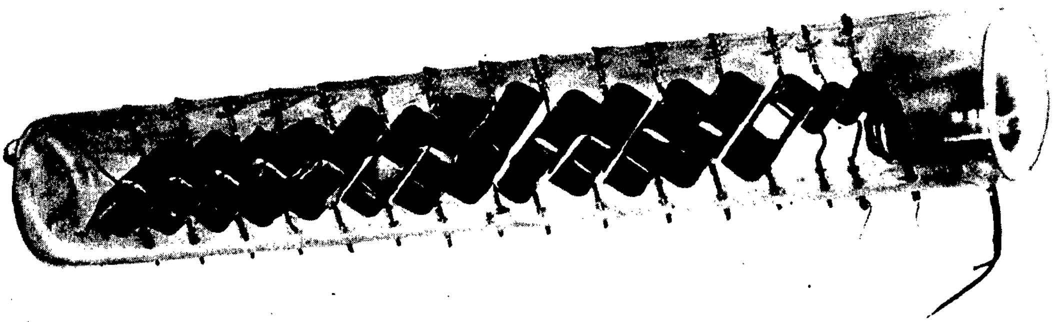


FIGURE 3. Thirty-stage multiplier.

finding the optimum voltage distribution among the dynodes.

One of the most interesting developments was that of a quadrant multiplier, each quadrant having 6 stages, as shown in Figure 4. These multipliers were built for Douglas Aircraft Company in order to detect radiation levels of 50 to 100 microlumens from distant sources presumably for use in tracking

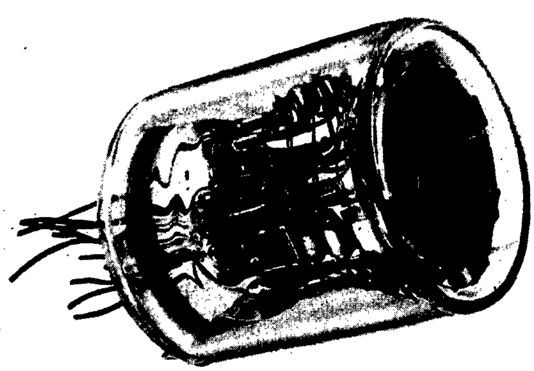


FIGURE 4. Quadrant multiplier.

equipment to follow such sources. In tracking, the differential output from opposite quadrants actuates servo mechanisms which keep the optical system pointed toward a target so that the target image stays almost centered on the origin of the quadrant coordinate system at all times.

In these tubes all of the quadrants are electrically connected, the four first stages together, the four second stages together, and so on except for the four collectors whose leads are brought out separately. The cathode is dish shaped, with the quadrants separated by "fences." The cathode diameter is 1¾ inches. The tube diameter is 2½ inches. The operating voltage is 1,200. The sensitivity is of the order of 200 ma per hololumen and the dark current is equivalent to that produced by 100 μhlm of radiation. Thirty-three tubes were built, 16 usable.

In addition, 23 NIR-sensitive vacuum phototubes with very large cathodes, 3x8 inches, were built for an Army contract. Sixteen were usable, with sensitivities between 20 and 33 μa per hololumen for tungsten light. Also some 40 NIR-sensitive vacuum phototubes, about 10 usable, were built for BuShips under a Polaroid Corporation contract. In these the cathode was evaporated on the glass bottom of a tube shaped like an Erlenmeyer flask 5 inches in diameter. These tubes were to be used at the focus of a mirror, supported by the neck of the flask, which passed through the vertex of the mirror. The responsivities were about 30 μa per hololumen.

Six gas-filled NIR phototubes, 2 usable, were made with 2x4-inch cathodes for Northwestern University under Contract OEMsr–990. Responsivities were 185 and 560 μa per hololumen at 100 volts with 0.01 hlm of incident flux.

Fundamental Studies

A number of fundamental studies were carried out in connection with the multipliers.

One involved the demonstration that if angles of acceptance of about 90 degrees or over are re-

quired, no optical system can give any substantial improvement in response, and the tube is best used without one.[21,31] This is a special case of the general angle-of-view theorem discussed in Section 4.1.3.[30a]

Another study concerned the optimum voltage per stage of a multiplier.[21] Assuming for simplicity that the multiplication per stage is proportional to the square root of the voltage, it was shown that the maximum overall gain with a large number of stages and fixed total voltage is obtained when the multiplication factor is $\sqrt{e}$ (base of natural logarithms) or 1.65; this means a much higher number of stages than are customarily used. This conclusion was checked with the 1-foot, 30-stage multiplier shown in Figure 3 and found to be correct as long as the output signal is small.

Other discussions have been given [21] of the influence of load resistor and space charge on the available output, and of the proper division of amplification between a multiplier and a following thermionic amplifier.

Several devices were constructed or assembled for measuring sensitivity and noise of tubes. They included a modified Macbeth illuminometer, a noise box similar in principle to the photocell test set (Section 3.3.1), and equipment for measuring noise from oscillograph traces.

Present Status

Farnsworth Contract OEMsr-1094 was terminated in August 1945. Some further needed work on photomultipliers for military use is presumably being carried out there under a succeeding Navy (BuShips) contract with Farnsworth.

Recommendations

The achievements made under the contract in improving multiplier design and performance were considerable and should not be lightly dismissed, since the techniques involved are very exacting and difficult to reproduce in large-scale production.

It is felt that the Armed Services ought to maintain educational orders in NIR phototubes and photomultiplier tubes of various types at all times so that a background of developmental and manufacturing experience may be built up and suitable types of tubes be made available when needed.

3.3 PHOTOCONDUCTIVE CELLS

3.3.1 Cashman Thallous Sulfide [TF] Cells

The other type of selective photosensitive detector intensively studied by NDRC was the photoconductive cell. Because of its great undeveloped possibilities, the emphasis on this type of cell was strong from the beginning and became much stronger after the Cashman TF cell began to be made successfully. Eventually more of the NDRC work was devoted to the TF cell than to all of the other photodetectors together.

Though thousands of papers and hundreds of patents have appeared on photoconductive cells in the last 50 years, few cells have been commercially marketed for the reason that most of the early ones were unstable when subjected to voltage or strong light. This problem has at last been solved and the way to large-scale commercial manufacture of the TF cell and related types is now open.

Initial State of the Art

Case Cells. In 1917, T. W. Case discovered photoconductivity in a thallium-sulfur compound containing oxygen.[1,3] Cells made from this compound were early turned to military applications in the voice and code signaling and communication systems described in Section 4.2.2. They were marketed commercially during the 1920's as Case Thalofide cells.

In making a cell, thallous sulfide which had been previously heat-treated was smeared in a layer on a quartz disk in air at elevated temperatures. Since the resistivity of the material is high, the resistance of the cell was reduced by shaping the contacts into coarse comblike grid patterns intermeshing with each other. These contacts were of lead sprayed through a stencil with a metal-coating pistol.

The measure of sensitivity of the cells was the change in resistance produced by exposure to a known illumination level from a tungsten lamp operating at an unspecified temperature. The original resistance of Case cells was 100 to 500 megohms. This decreased by a factor of 2 in the average cell (type RL) on exposure to 0.25 footcandle. Exceptional cells (type SRL) decreased by this factor on exposure to only 0.06 footcandle.

This initial sensitivity was fair and was fre-

quently not greatly exceeded by currently produced TF cells, but the stability of the cells was poor. They were sealed in red glass and the user was instructed not to expose them to more than 0.5 foot-candle; exposure to ultraviolet light or even a few hours' exposure to room light might destroy their sensitivity permanently.

The maximum spectral response of these and similar cells is near 1 μ, with a long wavelength threshold near 1.3 μ. Usually a secondary maximum is indicated near 0.5 μ but there is some suspicion that this is the result of drift and instability and may be spurious.

Other Work. The high NIR response and the incomplete disclosure of the process of manufacturing the Case cell stimulated research on such cells in many laboratories. The most extensive work was carried out by Majorana and Todesco in Italy; by Dubois and Fournier in France, who developed a cell later manufactured by the CEMA Company; and in Germany by Sewig, whose cells were developed in the Osram laboratories.[1,3] Russian and Japanese developments have also been reported.

Most of these authors believed the instability to be an inherent property of the thallous sulfide cell. Their cells were all much like the Case cell. As far as the literature reveals, the sensitive material was always Tl_2S, containing only slight, if any, excesses of Tl or S, and combined with oxygen in an unknown way.

German Cells. A few German thallous sulfide cells, intended for use in light-beam telephone systems, were captured during the war and were studied by Northwestern University under Contract OEMsr–235 and by University of Michigan under Contract NDCrc–185. Except for their small size, adapted for use in a narrow-beam stationary system, and the absence of a conducting grid, they appeared to be not very different as to method of fabrication from the cells just described. On a comparative basis they were certainly no better in overall characteristics than Cashman cells being made at the time. The sensitive areas were all small, from 1 to 6 millimeters square, and were mounted on the back of a protective red glass filter inside an unevacuated plastic capsule. Apparently they had all been made some years earlier and had been generally replaced more recently in German military equipment by lead sulfide cells of similar design.[12,13,14]

British Cells. During World War II, the development of thallous sulfide cells was also undertaken by the British Admiralty Laboratories. The British and American programs were kept in step for some time by a fairly effective liaison program. The British techniques were originally superior, but were eventually surpassed in this country. Some of the final British photosensitizing processes and cell designs were adapted from the Cashman processes and designs. Approximately 650 British cells were sent to the University of Michigan under Contract NDCrc–185 during 1943 and 1944 for testing prior to their being accepted for use by the U. S. Navy. Subsequently this contract furnished a photocell test set (see Section 3.3.1) and designs for it to the British.

Many of the British cells were excessively noisy, and their average S/N ratios never came up to the averages finally obtained on cells produced by Northwestern University under Contract OEMsr–235.

Course of Development

The Cashman TF cell is not greatly different in basic design from the Case Thalofide cells, but the manufacturing techniques have been highly refined and standardized. The quality is less variable from cell to cell and the individual cells are much more stable. The loose confusion of the names of these two cell types, which has crept into some reports, is to be deplored.

Military Interest. Two specific military problems were associated with the first NDRC interest in thallous sulfide cells. The first was the detection of night-bombing planes by NIR radiation reflected back from them (Reference 39, Chapter 4). The second was the need for detection devices in an NIR recognition and signaling system (Section 5.2). Both problems were studied by the University of Michigan under Contract NDCrc–185, under Navy Project Control NS–151 and later under SC–5.

The tremendous enlargement of military interest in the TF cells during the course of the work is reflected in the numerous additional project control numbers eventually assigned to their design, procurement or production, and testing. Number NS–225 was concerned with the procurement of British cells by BuShips and with the testing of them under Contract NDCrc–185. Numbers NS–159 (see Section 4.4.2) and AC–226.01 were concerned with in-

frared work in general. Other numbers dealt with specific military devices being developed under NDRC in which TF cells were used: NA–194 (see Section 5.3), AC–101 (Section 5.3), NA–191 (Section 5.5), AC–226.03 (Section 4.4.3), and AC–226.04 (Section 4.4.4).

Some of these devices used the TF cell as an NIR detector for code communication or signaling. One used the cell in locating a distant optical unit by reflected light (Section 5.4). Another used the cell in a positional indicating system (Chapter 7). Several devices made use of the cell as a voice detector after it was discovered in 1944 that the cell would give good S/N ratios at frequencies up to 3,000 cycles.

The possible use of thallous sulfide in image-tube presentation was investigated,[3] and the sensitivity of TF cells as thermal detectors was measured,[10] but there was not enough effect in either case to compete with materials of other kinds already being used for these purposes.

History of Development. The NDRC work on thallous sulfide cells stemmed from a program of basic research on semiconductors which had been begun by R. J. Cashman of Northwestern University in the spring of 1941 and which was privately resumed by him for a few months in the fall of 1941. This work was at first concerned with the question of whether semiconductors could be evaporated in a vacuum without decomposition, and favorable results had been obtained with Tl_2S and some other compounds.

These studies were continued under Contract NDCrc–185 at the University of Michigan in the summer of 1941, with special emphasis placed on attempting to produce stable and sensitive thallous sulfide photovoltaic cells. Sensitive cells were obtained, with responsivities of the order of 7,000 μa per hololumen, but they were not stable and suitable amplifiers for low-resistance cells of this type were not then available.

About this time some tests with a Case Thalofide cell, kindly furnished by W. W. Coblentz, showed it to have remarkable NIR sensitivity. Attempts were therefore made to manufacture some photoconductive cells and after some promising preliminary results had been obtained, Contract OEMsr–235 was set up at Northwestern University in December 1941 with the principal object of producing TF cells as sensitive as the Case cell, but with greater stability and adapted to mass production.[1,2,3,26]

A cell was visualized, as a goal to be achieved, which would have the following characteristics.

1. Stability.
2. High responsivity.
   a. High signal response.
   b. Low noise.
3. Dark resistance of 10 megohms or less.
4. Rugged construction.
   a. Nonmicrophonic.
   b. Vibration- and shock-resistant.
5. Good frequency response.
6. High relative NIR responsivity.

The stability and rugged construction were especially important for military applications.

It was expected that the stability would be the most difficult characteristic to obtain. The initial method of attack on this problem involved the study and systematic variation of variables in the manufacturing process to find the most favorable combination. Almost from the beginning occasional stable and sensitive cells were made, but their production did not become reproducible for many months.

The *photocell test set* equipment for testing the responsivity and noise of the cells was produced in the fall of 1942 by the University of Michigan under Contract NDCrc–185.[23,24,25] Much effort was spent thereafter in determining the cause and cure of high cell noise.

Supplemental and coordinated fundamental and theoretical studies of the cell properties were begun in June 1943, under Contract OEMsr–1036 at the Massachusetts Institute of Technology,[6,7,8] as this aspect had previously been somewhat neglected because of the pressure for cell production. It was hoped that these studies, together with the earlier work under Contract OEMsr–561 on the less successful selenium cell (Section 3.3.3), would throw light on the nature of the photoconductive processes involved and aid in determining optimum conditions for successful TF cell production. These studies were continued until June 1945. Some similar investigations were also undertaken at the University of Michigan.[2,9]

Consistently good activated thallous sulfide material was being made at Northwestern University by the beginning of 1944, and the average yield of good

cells was being rapidly improved. The design of the cells for use in the signaling system described in Section 5.2 was standardized soon thereafter. This design, later called type "A," had a sensitized grid area of $\frac{3}{4}$x$\frac{3}{4}$ inch located directly on the inner wall surface of the evacuated cell, rather than on a separate flat glass plate in the cell which had previously been considered necessary for the signaling application. This simple and nonmicrophonic design was patterned after some cells which had been made by Cashman in 1941 and has the advantage that the layer is sensitive to radiation from both sides and thus gives a 360-degree, or all-around, view. It apparently served as the basis for the design of the British ARL type S/T thallous sulfide cell.

By February 1944, the yield ratio of good cells had reached about 90 per cent of the number being made. For these type A cells, the reduction of resistance on illumination by 0.25 footcandle of tungsten lamp radiation was by factors of 10 to 30 as compared with factors of 2 to 8 for Case Thalofide cells. The S/N ratios of the type A cells, measured on the photocell test set (see below) averaged about 58 db for 1 μlm chopped 90-cycle unfiltered signal from a tungsten lamp operated at 2848 K color temperature. A 15-minute exposure to direct sunlight and a 15-hour polarization test with 22.5 volts across the cell in the dark were incorporated as standard stability tests on all cells.

By January 1944 it was felt that the original objective of designing a TF cell suitable for production had been achieved, and Contract OEMsr–1322 was then initiated at GE to set up facilities and develop manufacturing techniques for quantity production of type A cells.[4] This freed those working under Contract OEMsr–235 for the construction of

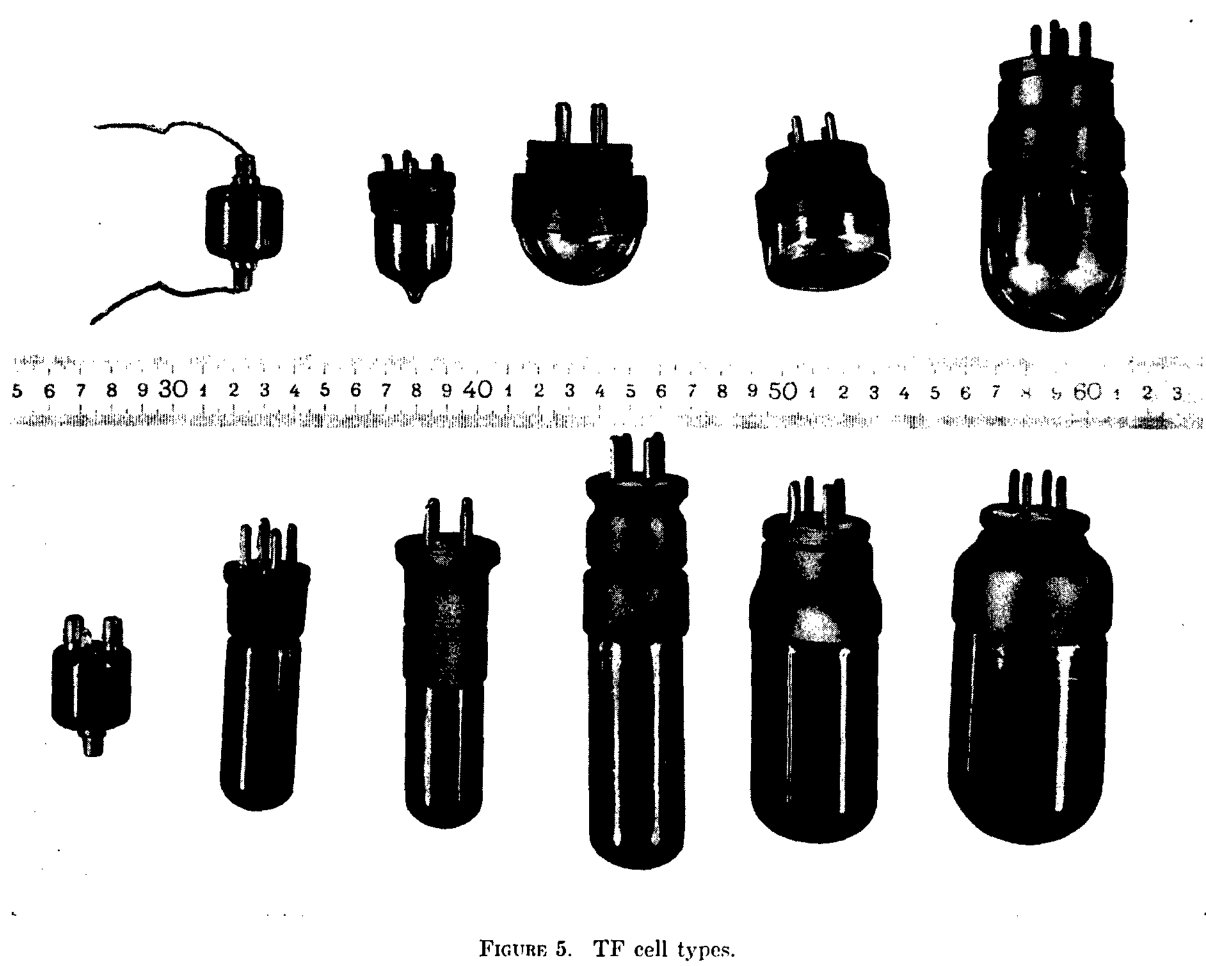


FIGURE 5. TF cell types.

cells of special design and the investigation of new cell materials as described in Section 3.3.2.

Actual quantity production of type A cells was taken over at GE by Navy contract in late 1944. Meanwhile the voice reception properties of the TF cell had been discovered and TF cells of a larger size, 1¼x2⅛ inches in sensitive area, were being used in the voice communication system of Section 4.4.2. This size was called the type B TF cell and was later given the RMA type number 1P38. In April 1945, a project for the development of the manufacturing techniques for the type B cells was begun by RCA under Contract OEMsr–1486.[5]

Various groups, especially those working on the military devices described in Chapters 4, 5, and 7, have compared the TF cells with different kinds of photoemissive cells. Theoretical studies relating to the TF cell properties have been made by some individuals besides those assigned to this work.[28,29,30a,30b]

By the end of the war, the minimum Navy acceptance specification for the type A cell was 48 db S/N ratio per microhololumen, as measured on the photocell test set, with 2.5-millimeter Corning 2540 filtered signal; it was 46 db for the type B cell. On the same test, average values for cells produced at Northwestern University were 56 db for type B, 58 db for type A and 68 db for a large number of ¼x¼-inch cells produced for various special purposes. On the same test, a sensitive but rather noisy 900-megohm Case Thalofide cell with 2-square centimeter area gave 21 db S/N ratio, but this figure may be 20 to 40 db too low because the test set is not designed for such high-resistance cells. The TF cells were being used quite confidently in experimental equipments designed for daylight operation and for continuous exposure to direct sunlight (Section 4.4.4). Most cells withstood application of 90 to 180 volts continuously without objectionable noisiness or loss of sensitivity.

The threshold sensitivity (signal equivalent of noise) of the cells is about equal to that of the best NIR phototubes in the best circuits developed during the war and is 10 to 30 times better than that of these phototubes when used in conventional circuits.

Description of Cells and Production Methods

Cell Types and Construction. Eleven different TF cell types made under Contract OEMsr–235 are shown in Figure 5.

The cells are made by evaporating a few milligrams of prepared and preoxidized Tl_2S in vacuum onto a comb-shaped intermeshing grid made of Aquadag (colloidal carbon) painted on the inner wall of the cell or on a glass plate (Figure 6). The cell is of Nonex glass. The grid lines are extended so that they will make contact at gold-plated tungsten lead-ins. In the cells shown in Figure 1, the size of the sensitive grid area varies from ¼x¼ inch to 2x3 inches, and could be made still larger. The grid spacing is from 15 to 25 lines per inch.

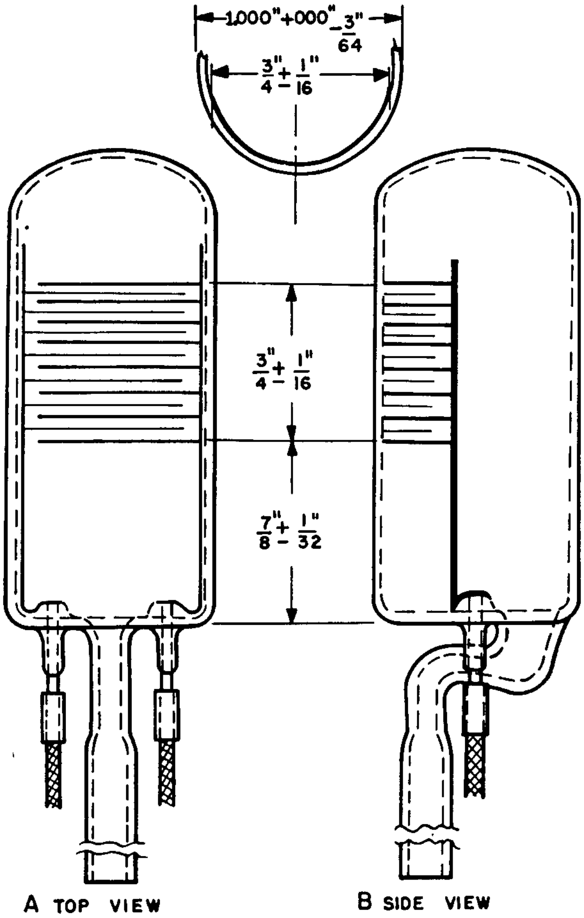


FIGURE 6. Diagram of unbased TF cell.

After evaporation, the Tl_2S layer is sensitized by baking for 20 minutes in an oven at about 270 C in the presence of about 200 μ pressure of oxygen and 15 μ pressure of water vapor. After the cell has cooled to room temperature, the remaining gas is pumped out to at least a 2-μ vacuum and the cell sealed off.

The cells are cemented in spun aluminum four-

prong standard bases having an isolantite insulator coated with moisture-repellent lacquer.

Successful cells can be made only if meticulous care is exercised in the purification of the Tl_2S and other components and in the cleaning of the glassware.

Summary of Cell Characteristics. Some properties of the cells are summarized in Table 1.

measure of the low-level response of a cell. The latter response is best measured on the photocell test set. For the standard 1-μhlm 90-cycle NIR-filtered signal, a type A cell, with matched load resistor and 90 volts applied across both, gives about 72 db signal output and about 14 db noise output in a 1.8-cycle band-pass, referred to a 0-db level of 1 μv rms. The S/N ratio is thus some 58 db. Without the Corning 2540 filter (2.4 mm thick) it increases about 13 db. The 90-cycle signal does not correlate very well with the response to steady light but is very satisfactory for predicting the response at higher frequencies up to about 3,000 cycles.

TABLE 1. Properties of some photoconductive cells.

Property	Cell Type					
	Case Thalofide	TF ¼ x ¼ in.	TF type A ¾ x ¾ in.	TF type B 1¼x2 in.	PbS* ½ x 1 mm	PbS ¼ x ¼ in.
Area (sq in.)	0.3	0.06	0.6	4	0.0008	0.06
Grid spacing (in.)		1/25	1/25	1/15	No grid	1/25
R_d (megohms)	300	19	6.1	3.5	1,20	1
S† for 10^{-6} hlm filtered (db)		89	72	64.5	90,91	55
N† for 1.8-c bandwidth (db)		21	14	8.5	26,3	8
S/N† (db)	21‡	68	58	56	64,88	47
Signal equiv. of noise filtered† (hlm)	‡	4×10^{-10}	1.3×10^{-9}	1.6×10^{-9}	6×10^{-10} / 4×10^{-11}	4×10^{-9}

* First figure, room temperature; second figure, dry-ice cooled.
† Signal and noise from photocell test set under standard conditions.
‡ Test set not designed for high-resistance cells.

The resistance of the cell when in total darkness (dark resistance) can be controlled by variations in manufacture and is usually set to reach a stable value of between 0.5 and 20 megohms after a few days' aging. The capacitance of a type A cell is about 20 μμf.

Figure 7 shows the spectral response curve of a cell made at an intermediate stage of the development, together with the curve for an S_1-surface phototube for comparison. In later TF cells, the threshold was extended to 1.45 μ and the response curve was almost flat from 1.2 μ to below 0.4 μ, probably being limited on the short wavelength side only by the Nonex wall transmission. There is good sensitivity to X rays.

One method of measuring the cell response to integrated light over the wavelength range to which it is sensitive is to determine the factor by which the resistance decreases on exposure to a standard flux from a tungsten lamp. For type A TF cells, the factor is 10 to 30, with 0.25 footcandle illumination level.

This method involves high intensities, bringing in saturation effects, so that it gives only a crude

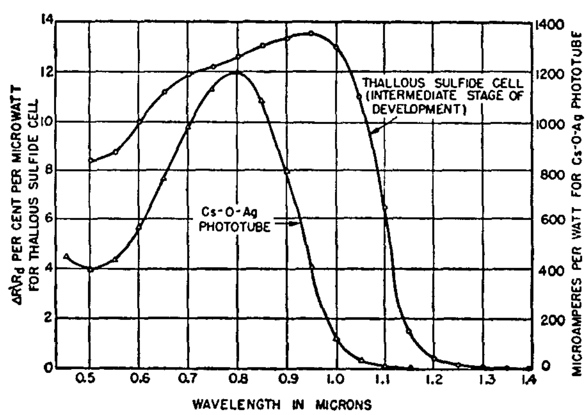


FIGURE 7. TF cell and phototube, S_1, spectral responsivities.

The signal and noise are both functions of cell area as discussed later under "General Properties."

In testing, the flux is normally spread over an

area of about ½-inch diameter on the cell. Theoretically, the signal output for a given flux should be independent of the spot size into which the flux is concentrated, but in practice saturation and grid-line effects invalidate this rule as the spot is made smaller.

The voltage signal output as a function of incident light flux, with the load resistor matched at every illumination level, is shown in Figure 8. It is linear from the threshold up to about 120 db output level, which corresponds to a flux of about 10

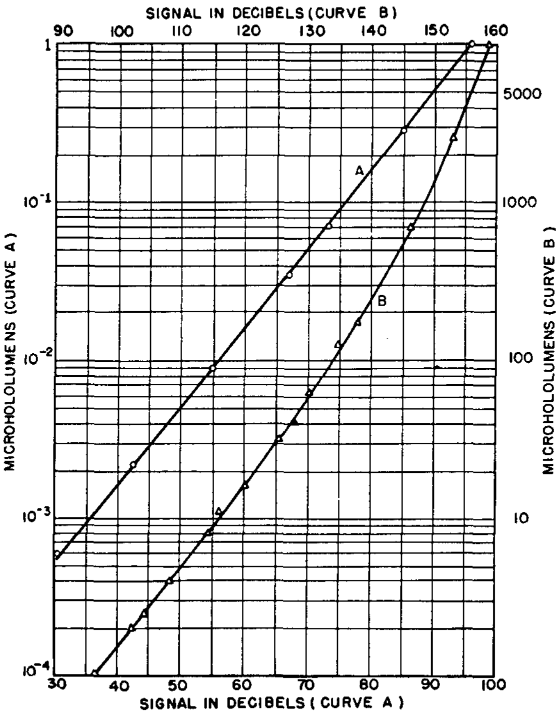


FIGURE 8. TF cell response versus incident flux level (modulated).

µhlm for a typical cell; the linearity thus extends over a range of about 10^5 in flux. The upper limit depends on applied voltage, load resistor, signal frequency, and waveform, amplifier performance, etc., so that the linearity of the fundamental photoprocess in the cell itself may extend to even higher flux levels.

The signal and noise are both approximately proportional to the applied voltage and inversely proportional to the frequency (for constant amplifier bandwidth) as shown in Figures 9 and 10, so that the S/N ratio of TF cells is almost independent of either voltage or frequency up to about 3,000 cycles where these relations begin to fail. The important voice frequencies near 1,500 cycles may thus be detected with good sensitivity by TF cells.

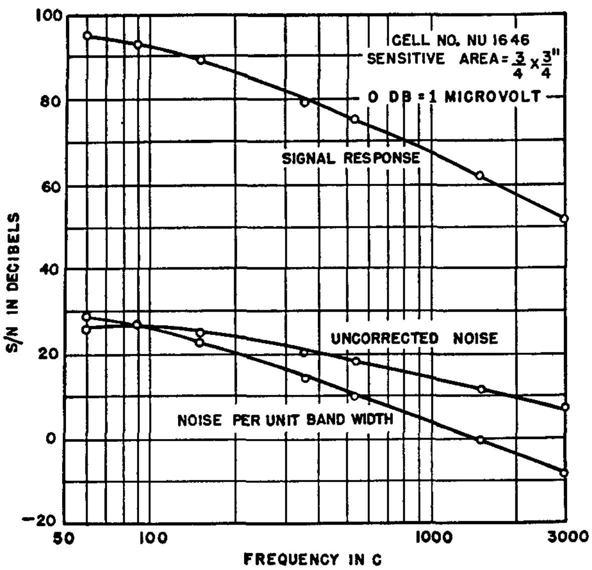


FIGURE 9. TF cell signal and noise as functions of frequency.

The stability of the cells with respect to voltage or strong light has already been stated. On exposure to strong steady background light, the most obvious effects on the cell are great decreases in resistance,

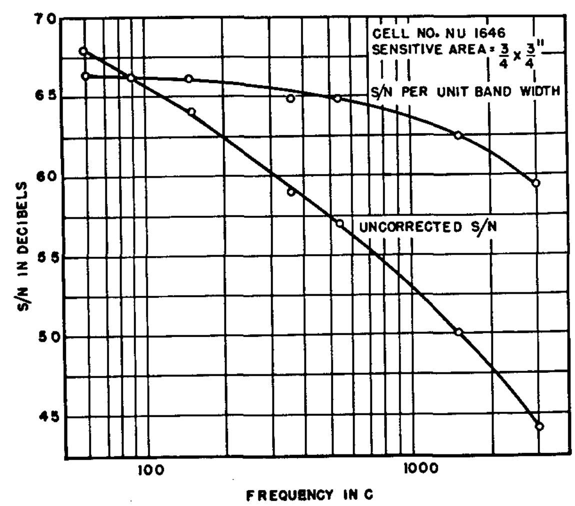


FIGURE 10. TF cell S/N ratio as function of frequency.

in signal, and in noise. Part of the decrease in signal and noise is due to the change of resistance and resultant mismatching of the original load resistor, but even after the load resistor is readjusted to the

new conditions, great losses in signal and noise and in S/N ratio may still remain. One experiment, described in Section 4.4.4, was made on the effects of exposure to a background equivalent to about 1,000 footcandles of light from the overcast north sky. The resistance of a type B TF cell changed from about 2 to about 0.05 megohm; the loss in S/N ratio, even with the load resistor properly adjusted, was about 20 db. Although this loss is serious for military equipment which might be needed in daylight work, it is small compared to the losses produced in phototubes by background light.

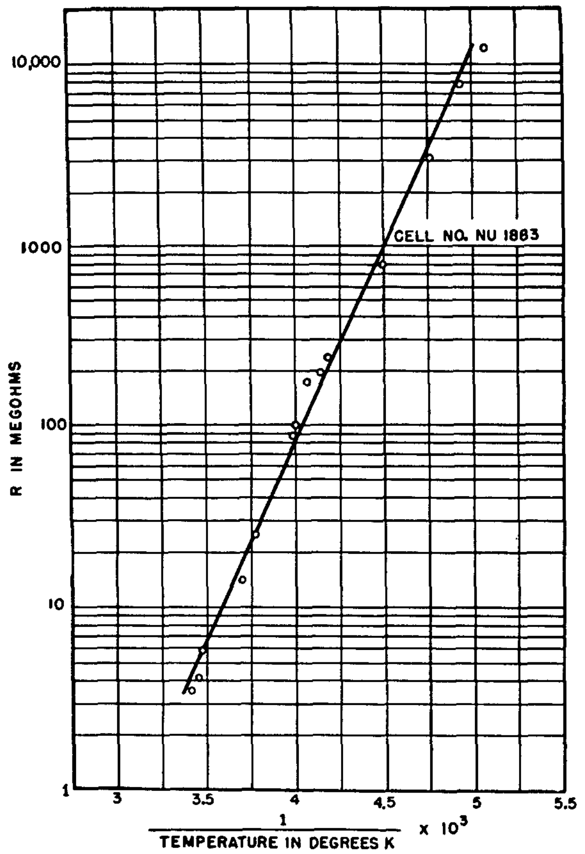


FIGURE 11. Resistance of a TF cell versus temperature.

The resistance of the TF cell is strongly dependent on temperature, increasing at lower temperatures according to the usual exponential law for semiconductors (Figure 11). The S/N ratio is less affected. If the load resistor is properly adjusted at each temperature, the ratio appears to increase by a few decibels on going from room temperature to 0 C and then to decrease at lower temperatures.

Much effort was spent by Northwestern University under Contract OEMsr–990 [30] and by the University of Michigan under Contract NDCrc–185 on the design of the best circuit for use with a TF cell. The resultant designs are described in Sections 4.4.2 and 5.2. The essentials appear to be the use of a cathode-follower in the first stage, which must be located no more than a few inches from the cell; and the use of a wire-wound or equivalent low noise resistor for the load resistor of the cell. Careful electrical shielding may also be needed around the cell to prevent pickup from stray fields. With such a circuit it is possible to have a photodetecting threshold limited only by the inherent noise of the TF cell itself.

Comparison with NIR Photoemissive Detectors. Comparisons were made between TF cells and various photoemissive devices as NIR detectors by several groups, but perhaps the most elaborate were those by Northwestern University Contract OEMsr–990 reported under "Choice of Photodetector Cell" and "Interrelations of Components," Section 4.4.2.[30] The conclusion of this contract was that, with the best type of circuits tried for each type of detector, the average threshold sensitivity of type A TF cells at 1,500 cycles was equal to that of the best of the many other photoemissive devices tried, namely, Continental Electric Company type CE–1–AB gas-filled phototubes. This held true with either cesium-vapor or continuous-spectrum sources, NIR filtered or unfiltered, within 3 or 4 db one way or the other.

The conclusions of this contract do not agree with those of any other group, as they show the cesium-surface phototube in an unusually favorable light. This is probably the result of the unusual properties of the phototube circuit developed by this contract, which has no external load resistor, using instead only the grid-to-cathode impedance of the first preamplifier stage to produce a voltage drop when the photocurrent flows. This circuit was more sensitive by a factor of 10 or more than the conventional circuits which were tried, and appeared to have a threshold limited only by the inherent dark current shot noise of the phototube itself. Those working under other contracts, such as OEMsr–1073 of the University of California (see "Receiver" in Section 4.3.2) gained an advantage of 20 to 30 db in changing from phototubes to TF cells in a voice communication system. Northwestern University under Contract OEMsr–235 found the

gas-filled CE–1–AB phototubes mentioned above, when used with a 10-megohm load resistor, gave 10 to 40 db lower S/N ratio than the final type A TF cells, both types being measured on the photocell test set at 90 cycles with unfiltered tungsten light.[3]

The TF cells have other advantages over a cesium surface phototube. One is the higher ehT° values for a given NIR filter as a result of the longer wavelength threshold (see Figure 7 and Chapter 2). Another is the all-around view of the TF cell, with its layer formed on the glass cell wall where it can receive light from both sides. Still another is the complete absence of microphonics, the TF cell having no internal parts between which relative motion can occur. Also, the TF cell is comparatively indifferent to humidity and moisture, since surface leakage resistances of the order of 20 megohms or more, which would form a serious shunt across the best photocells, have scarcely any effect on TF cell output. This was one of the main reasons for abandoning phototubes in the voice systems described in Sections 4.3.2 and 4.4.2.

The TF cell output, with properly matched load resistor, is seriously affected by background light but not so seriously as the output of a phototube, so that the TF cell is better for use as a detector in equipment which must operate in daylight. Still another advantage is to be found in the reproducibility of these desirable characteristics in TF cells, which can be constructed on a large scale with a mean deviation of about ±4 db in filtered S/N ratio, compared to two or more times this deviation for phototube production. Great variations in size of the TF cells—from 0.06 to 4 square inches in the group shown in Figure 5—can be made without alteration of the cell properties, as these are unrelated to the size of the surface.

Disadvantages of TF cells for some purposes will be found in their nonlinearity at high light levels, and in the strange behavior of signal and noise with frequency and background light, especially the loss of threshold sensitivity at frequencies over about 4,000 cycles.

Details of Manufacture

Construction of Cell Bodies. The cell is made of Nonex so that it will stand the 450 to 500 C temperatures of the Tl_2S evaporation and so that it can be sealed directly to tungsten lead-ins. The type A envelope is made of selected 1-inch diameter Nonex tubing with walls 20 to 40 mils thick. Other glasses and lead-ins could be used if tubing of the proper sizes were available. Tubing is used instead of blown bulbs, because the bulbs obtainable during the war showed white deposits of B_2O_3 during working of the glass. The Tl_2S appeared to react unfavorably with this or some other constituent to form relatively insensitive brown nonuniform streaks over the walls and grid. These difficulties for some reason did not appear when tubing was used.

The grid lines may be drawn with a short ruling pen. The glass surface beneath the grid must have no surface cracks or striations into which the Aquadag might be drawn by capillarity to produce high local electric fields and noisiness in the cell.

Grids have been made not only with Aquadag but also with evaporated platinum and gold, with platinum, gold, and silver ceramic inks, and with a soft lead pencil. The metals occasionally reacted with the Tl_2S and so their use was discontinued; the lead pencil grids gave noisy cells. The Aquadag was therefore chosen as the best material.

Some observations at Northwestern and MIT indicated that the Aquadag may play an essential catalytic role in the oxidation-sensitizing of the Tl_2S layer, producing cells more sensitive but noisier than those made with metal grid lines. To keep the sensitivity but reduce the noise, some cells were made at RCA with Aquadag ruled over a metal grid;[5] their performance appeared promising but there was insufficient time to carry this study to completion.

A few cells have been made at Northwestern with multiple grids (two or four) in one envelope. Such cells may be useful in tracker systems (see Section 4.1.3 and "Special Tubes," Section 3.2).

The gold plating over the tungsten lead-ins is needed to make a good contact to the Aquadag; if it is omitted, the cell is more likely to be noisy.

The TF cell lead-ins are made of 40-mil tungsten rod, ½ inch long, butt-welded to an 8-strand copper and nickel braid. The heavy lead-in is needed only to give a large contact surface with the Aquadag.

Quite exacting routines have been worked out for the glass-working, cleaning, gold-plating, and ruling of grids, in order to avoid and eliminate contaminants, deposits, or blisters, which might cause open circuits, shorts, poor contacts, or noisy cells, or which might react with the Tl_2S unfavorably. For

complete details reference should be made to the contractors' final report on TF cell development.[3]

Preparation of Tl_2S. Highly purified thallous nitrate or sulfate is used as the starting material. This salt is converted to black amorphous Tl_2S by bubbling H_2S through an ammoniacal solution of the salt in conductivity water. After washing and filtering the precipitate, it is transferred to a vacuum desiccator, air being admitted after the second and fourth days just long enough to break up the chunks of Tl_2S to promote faster drying. After two weeks' drying, the material is allowed to stand in air of about 50 per cent relative humidity for at least 72 hours, the moisture catalyzing a slow oxidation.

Samples of approximately 30 grams are then fused in vacuum. Two phases appear, the lighter and more volatile being a yellow or red insulating layer which is some kind of oxide of the material, probably largely Tl_2SO_2. The denser phase has, on cooling, a crystalline metallic appearance and is Tl_2S within the limits of error of chemical analysis, but from its behavior toward photosensitizing it must contain appreciably more oxygen than Tl_2S prepared by synthesis from the redistilled pure elements in vacuum. The lighter phase is scraped off from the denser slug with a knife and discarded; the slug is crushed and stored in evacuated ampoules until needed for cell fabrication. Fifteen to 50 mg of the crushed Tl_2S are used in each cell, depending on the cell size.

Study of Variables in Preparation of Tl_2S and Sensitizing. The production of stable and sensitive TF cells was only achieved by Contract OEMsr-235 after months of study through 1942 and 1943 of many hundreds of systematic variations of manufacturing technique and of the effect of these variations on the cell characteristics. The variables were in two classes, those which concerned methods of preparation of the Tl_2S starting material and those which concerned sensitization of the layer after evaporation. They included

1. Thallous sulfide.
   a. Excess or deficit of metallic constituent from stoichiometric proportions.
   b. Impurities.
   c. Crystal size and orientation on receiving surface.
   d. Absorbed and adsorbed vapors and gases.
2. Cell structure.
   a. Contacts (grid).
   b. Receiving surface.
3. Oxidation.
   a. Oxidation of material before forming surface.
   b. Oxidation of material during or after forming surface.
   c. Effect of vacuum conditions (presence or absence of vapors and gases) on oxidation.
   d. Temperature.
   e. Time.

Previous literature on semiconductors such as phosphors pointed to the need of very pure starting materials and to the importance of the study of impurities. So the first variations were in methods of making Tl_2S. It was prepared by precipitation from a solution, followed by oxidation by moist air (the final method adopted). It was prepared by precipitation without oxidation. It was prepared by synthesis in vacuum from the elements, both with stoichiometric proportions and with regularly varied excesses of one element or the other. It was prepared by using elements purified by multiple distillation in vacuum; elements only commercially pure; and elements with known amounts of lead, copper, or silver impurity. More than 40 samples alone were prepared under Contract OEMsr-235 by synthesis in vacuum. At MIT, under Contract OEMsr-1036, thallium was also prepared electrolytically; Tl_2S samples were made with total impurities of less than 15 parts per million. In some cases all operations were carried out in an atmosphere of inert nitrogen.

The same exhaustive attention was given to every stage of cell manufacture. For the detailed list of the variations and of their effects on cell properties, reference must be made to the original reports.[3,6] Some of the effects, especially those produced by impurities, throw light on the theory of the photoconductive process but cannot be discussed in detail here.

The general results and conclusions were as follows:

For good cells, the metallic impurity had to be less than 0.5 per cent and high purity was preferable. The Tl_2S, however it was made, had to be prefused in vacuum before introduction into the cell

in order to avoid eruptive evolution of gas and consequent nonuniformity in the evaporated layer.

Material prepared either by vacuum synthesis or by precipitation from solution without subsequent oxidation gave much less sensitive cells than material which had had some exposure to air. The first excellent cells were obtained from some precipitated Tl_2S which had been inadvertently exposed to air in a leaky desiccator for several months.

Preoxidized samples required less oxidation-sensitizing after evaporation of the layer in the cell; a lower baking temperature sensitization was possible, and this was associated with lower cell resistance and better stability. The preoxidized samples evidently contained a trace of some substance important in their photoconductivity, even though chemical analysis showed them to be pure Tl_2S within the limits of error. Several experiments showed that this trace substance was indeed oxygen.

The best and simplest method of cell preparation was as follows: The glass cell blank, with the grid ruled and the end sealed off, was baked out in a furnace. The crushed Tl_2S was introduced and the cell sealed onto the vacuum pumping system with the grid uppermost and the crystals on the bottom of the cell. The layer was evaporated quickly by heating the cell wall with a torch.

Photosensitization of the evaporated layer only developed after exposure to oxygen at high temperatures. The pressure had to be between 20 and 1,000 μ, the temperature between 150 and 350 C, and the baking times between 10 minutes and 2 hours. The resistance of the unoxidized material is measured in thousands of ohms; for the completely oxidized material, which turns into a colored insulating layer of Tl_2SO_2, it may be thousands of megohms. For good cells, with a few megohms resistance, the average amount of oxygen taken up in sensitizing is 15 to 20 per cent of the amount needed for complete conversion to Tl_2SO_2. The X-ray and electron diffraction data of Contract OEMsr–1036 indicate that the photosensitive material is a solid solution of oxygen in Tl_2S. Sensitive layers are black or dark brown with a metallic appearance.

The effects of contaminating vapors were studied. Mercury was harmful to cell properties so that oil diffusion pumps had to be used on the vacuum systems. After much uncertainty and many misleading results it was established that water vapor was beneficial in sensitization, apparently playing a catalytic role in the oxidation. Absolute ethyl alcohol, hydrogen peroxide, and dioxane behave similarly. No sensitization occurs with water vapor only, in the absence of oxygen.

Although some elements of the cell preparation are very critical, others are not, and quite diverse baking and sensitization schedules were worked out at different laboratories.

Commercial Production: Special Studies. The development of commercial facilities for manufacturing TF cells at GE [4] and at RCA [5] led to variations only in minor details from the Northwestern University procedures already outlined. The first object of the commercial contracts was to break down the process of cell manufacture into small steps capable of being adapted to a production flow line and handled by technically unskilled operators. The second object, emphasized at GE, was to make cells which would withstand abuse in the field, such as short-time application of overrated voltage, brief exposure to sunlight, immersion in hot or cold water, temperature cycles, long-time immersion in water, exposure to salt spray, and dropping on the floor. Navy specifications on resistance of the cells to such treatment were worked out by consultation with all TF-cell contracts. These requirements led to special studies on basing cements, moisture-proofing varnish, and insulating wafers, among other things.

At GE, for controlling quality, a series of systematic tests was set up to be applied to all cells. These included: measurement of dark resistance at 25 C and at 0 C; change of resistance under 0.25-footcandle tungsten light; change of resistance (polarization) under 22.5 volts in the dark for 8 hours; S/N ratio on photocell test set; and inspections throughout each stage of manufacture on such points as location, size, and uniformity of grid, cleanness of cell, straightness of based cell, etc.

Several items of special apparatus were designed and built at GE. These included cell-cleaning and gold-plating baths, grid-ruling machines (seen in Figure 12; these are slightly modified from the original Northwestern design), exhaust and sensitizing units, basing devices, and a room with temperature and lighting regulation which contained the inspection and test equipment.

Over 8,000 type A cells, including rejects, were processed at GE before the NDRC contract was superseded by a Navy purchase contract. The ini-

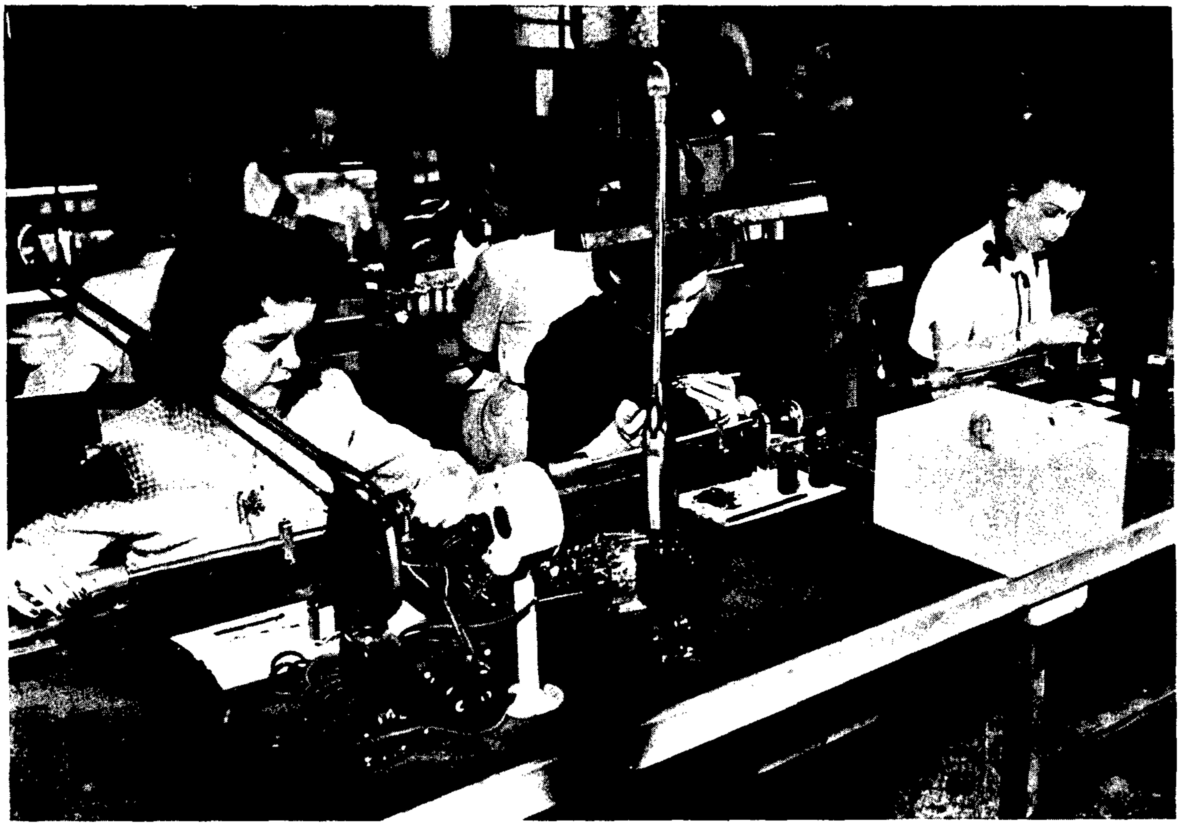


FIGURE 12. TF cell-ruling fixtures on General Electric assembly line.

tial Navy specification for minimum acceptable responsivity had been 38 db S/N ratio for a standard filtered signal from the test set; the average quality of the cells produced was improved enough so that it was possible to raise it to 48 db and finally 53 db before termination of the NDRC contract.

At RCA, studies were made on glasses and lead-ins other than Nonex and tungsten which might be suitable for the cells. Studies were made on ruling pens and on possible use of decalcomania and silk-screen technique for making grid lines. The question of mercury versus oil diffusion pumps was examined. An empirical formula was found which would represent the degree of oxidation of the Tl_2S layer as a function of temperature, oxygen pressure, and exposure time.

Since the RCA contract ran only about six months before being terminated as a result of the end of the war, only about 300 cells were processed in the laboratory (experimental) and about 250 in the factory (preproduction). At the end, the factory had facilities for production at the rate of 600 cells per month. The average S/N ratio (filtered) of the laboratory type B cells on the photocell test set was about 45 db.

Testing Procedures

The simplest test of photoconductive cell sensitivity is the measurement of relative resistance change under a standard hololuminous flux. For comparisons within a single laboratory, this flux needs simply to be reproducible. For interlaboratory comparisons, a tungsten lamp at a color temperature of 2848 K is chosen as the source, following the system of NIR photometry outlined in the Appendix. One-quarter footcandle was used as the standard flux in such tests, by tacit agreement. Unfortunately, this usually involves high-level nonlinear response; it does not indicate the response to modulated radiation nor does it give the dark current noise which determines the threshold sensitivity.

The nonlinearity problem also arises in determining the relative NIR responsivity of a cell. This is determined by measuring the ehT° of the cell for some standard source and filter combination, using the resultant figure as an indication of long-wave

response. But when nonlinearity is present, a complicated procedure is required, involving equalization of response with a source at different distances and use of the inverse square law, if an accurate value of ehT° is to be obtained.

Photocell Test Set. To get around these difficulties and to make possible accurate interlaboratory comparisons of TF cells, University of Michigan Contract NDCrc-185 constructed six photocell test sets in 1944.[23,24,25] Project Control NS-225 was applied to this program.

These instruments were designed to measure the modulated signal and noise output voltages from cells with resistances between 0.25 and 40 megohms. Since the main military use of the TF cells in 1943 was in the code communication system described in Section 5.2, the set was arranged to duplicate rather closely, when desired, the operating conditions of this system, while retaining a high degree of flexibility for other experimental adaptations.

The radiation from the calibrated tungsten source at 2848 K color temperature was interrupted mechanically by a "light chopper" or sector disk at 90 cycles (Figure 13). It could be passed, if desired, through a 2.4-mm thickness of Corning 2540 filter. After a great optical reduction of intensity by a known amount, the radiation fell on the cell. This was placed in a cathode-follower preamplifier and step-attenuator system with suitable indicating meters (Figure 14). The tuning of the system to 90 cycles and the band-pass, which was 1.8 cycles wide down 3 db, were regulated by a General Radio Company's sound analyzer.

The optical attenuation of radiant intensity was

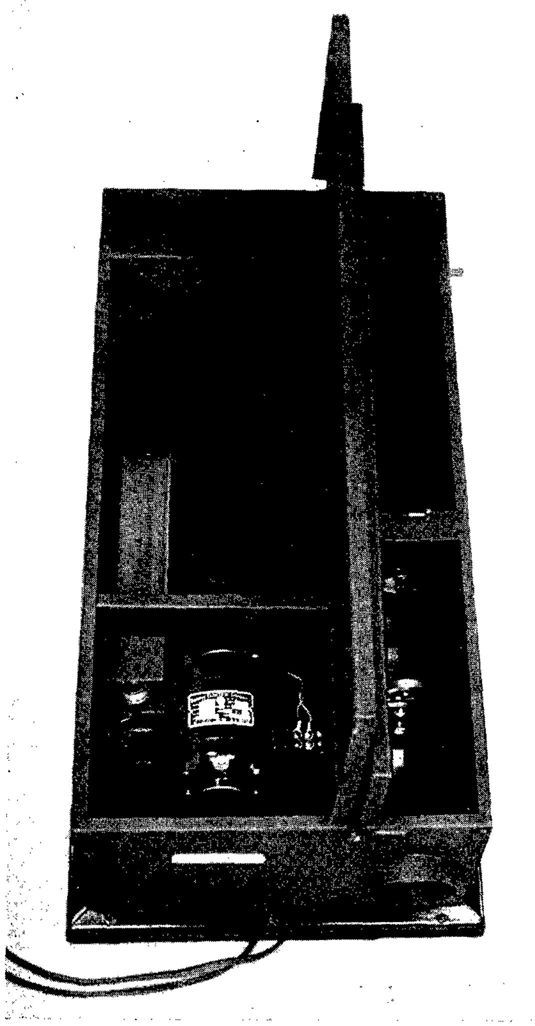


FIGURE 13. Microflux source box in photocell test set.

FIGURE 14. Electrical measuring equipment in photocell test set.

RESTRICTED

produced by forming a small image of the source by reflection from a convex surface. By varying the source distance and by interchanging a series of calibrated aperture stops in the beam, the incident flux on the cell could be regulated throughout the range of 1 to 100 μhlm. By moving a lens, this flux could be concentrated on a small spot or spread over a large area of the cell.

The electrical equipment was arranged to measure cell output voltages between 1 μv and 100 mv.

With this apparatus it became possible to measure the responsivity of a cell and its signal equivalent of noise. For a standard input flux, usually chosen to be 1 μhlm total swing as the light was chopped, the output signal could be measured in decibels above some reference level. The 0-db level was usually taken to be 1 μv rms. By measuring noise, then, the S/N ratio and the threshold could be determined. The ehT° for a filter could be determined by the loss of signal in decibels when the filter was placed in the path. The flux level was low enough so that nonlinearity problems did not arise.

Various adaptations and modifications were made on the test sets by the different contractors using them. These included the addition of sets of sectors with various numbers of openings for studying frequency response. Noise-frequency data could be obtained merely by varying the tuning of the sound analyzer, making proper corrections for bandwidth. In some sets, arrangements were made for introducing other modulated sources than the calibrated tungsten lamp or background sources, or for heating or cooling the cell, or for moving it around to find the most sensitive area. In some experiments the output of the amplifier was fed into an oscilloscope for study of the wave shape.

In order to reach the noise level of the cell itself, antivibration mountings had to be installed on the preamplifier box which contained the cell. This box had to be mechanically insulated from the box containing the running motor, the cell had to be placed inside a double electrical and optical shield, and finally it was necessary to replace all composition load resistors by wire-wound resistors because of their lower noise.

The usual reproducibility of interlaboratory comparisons of a given cell on different test sets was within ±2 db, which is about the reproducibility for the same cell after being taken out of a set and put back in again. The lack of complete reproducibility is due partly to strange long-period components in the TF-cell noise, which make it difficult to read the meters to closer than ±2 db, and partly to differences in sensitivity over a cell surface as the flux distribution or the angle of incidence varies.

These test sets were furnished to University of Michigan Contract NDCrc-185, to Northwestern University Contract OEMsr-235, to the General Electric Company Contract OEMsr-1322, to the Naval Research Laboratory, to the Board of Engineers at Fort Belvoir, and to MIT Contract OEMsr-1036. After this last contract was terminated, its set was overhauled under Contract NDCrc-185 and furnished to RCA Contract OEMsr-1486. The electrical measuring portion of the test set together with complete blueprints and specifications for the microflux source were furnished to the British Admiralty Research Laboratory. In addition, specifications for the test set were furnished to Farnsworth Contract OEMsr-1094 and provided the basis of the equipment constructed by that contract for the testing of photomultipliers. These specifications for the complete test set were also furnished to Wright Field.

The sets proved to be indispensable in the study of variables and maximizing of performance during the TF-cell and PbS-cell development, in the standardizing of interlaboratory comparisons, and in the maintenance of quality during production. They were and they remain the most valuable and the most commonly used instruments for the study of the properties of photoconductive and other related cells.

General Properties

Some general properties of TF cells will be discussed before going on to the more fundamental and theoretical studies.

Resistance. Cells of different sizes activated in the same way, with the same starting material, layer thickness, and grid spacing, should have a dark resistance inversely proportional to the grid area. By using selected Tl_2S starting material and slightly varying the activation schedules, it is possible to exert some control over the resistance without serious loss of responsivity. Low resistance is achieved by less oxidation [6] and lower oxidation temperature.[3] Low resistance cells generally have lower signal response, lower noise, and better stability than higher resistance cells.

The degree of control of resistance attained in production of good cells is shown by the figures on various cell properties collected in Table 1. The largest and smallest Cashman cells have a ratio of areas of about 60, but the dark resistances differ by a factor of only 6. The ¼x¼-inch cell is about as small as can be made with good sensitivity if the resistance is to be kept under 20 megohms.

Spectral Response: Filters. The curves of spectral response in Figure 7 were taken by Contract OEMsr–235 with a Van Cittert double glass monochromator, with the radiant flux measured by a calibrated thermocouple. The sensitivity of a ¼-inch TF cell is such that the current produced by the resolved radiation may be measured with a microammeter.

The conditions of measurement of the curves in most studies made do not guarantee a linear response of the cell and associated circuits, so that probably the curves are relatively too low where the incident intensity is greatest, near 1 μ. This nonlinearity does not affect the location of the threshold and peak response points but makes it impossible to compare measurements taken on different instruments. Contract OEMsr–235 worked out a method of correcting for this nonlinearity.[3,6] Heating effects, drift of response with applied voltage and time, and possibly hysteresis, are additional sources of error in TF-cell spectrometry, which may largely mask the true variations from cell to cell and from time to time on the same cell. The effect of cell temperature on spectral response curves is probably small, but needs study. Much more careful spectral response measurements, under controlled conditions at low light levels, such as to guarantee linear response, are greatly needed.

Since the photoconductive effect begins in the spectrum between an absorption band at short wavelengths and a transmission band at long wavelengths, much of the decreasing response of the cell at long wavelengths is due to the failure of the layer to absorb the radiation. Thus, a TF cell absorbing 99.9 per cent in the visible may absorb only perhaps 70 per cent of the incident radiation at 1 μ, and much less at longer wavelengths.[3,6] A thicker layer absorbs more than a thin one and thus has a substantially better long-wave response. This is shown by the effective holotransmission of the Corning 2540 filter on the test set; this filter may give a loss of signal of 15 db with a visually transparent TF cell but only 12 db with an opaque one. However, layers too thick do not make good cells as they are difficult to sensitize.

Computed and observed TF-cell ehT values for many different filters and sources have been given in Chapter 2. The computed values are based on a spectral response curve (Figure 7), taken for convenience as an arbitrary standard, of a TF cell in an intermediate stage of the cell development program.

Linearity. Early reports on nonlinearity of the TF-cell response as a function of incident flux were exaggerated and were largely due to poor choice of a parameter for measuring response. The fundamental photoprocess in the cells is the creation of new conduction electrons, and so the proper response parameter is the change of cell conductance, or the change of current for constant applied voltage, as pointed out by MIT Contract OEMsr–1036.[6] Though plots showing change of resistance, or of voltage or current, when the cell is in series with a load resistor, are important in amplifier discussions, they are bound to be nonlinear. Plots of conductance also appear to be nonlinear above flux levels generally accepted as about 10 μhlm or about 0.1 μw at wavelengths near 1 μ, but care must be exercised if the internal cell effects are not to be masked by heating or amplifier nonlinearity. The curvature in Figure 8 may possibly be from the latter cause.

Though nonlinearity is found at comparatively low levels, complete saturation is not reached, and there is still some sensitivity left, even in direct sunlight.

Almost all plots of comparative linearity of response as a function of wavelength or temperature [6] or as a function of cell sensitivity [2,3] have shown that the curvature of the plots depends only on the output current and not on the incident intensity. This is to be expected regardless of whether the nonlinearity is due to the poor choice of response parameter, to the external circuit, or to processes in the cell itself, and so throws no light on the site of the nonlinearity. The equivalence of photocurrent behavior for different wavelengths does confirm what was already assumed, that all conduction electrons are equivalent, regardless of how they are initially produced.

This equivalence even appears to extend to the PbS cell. This cell has a greatly extended region of linearity in plots of output versus incident flux, as

compared to the TF cell. Probably this extra linearity, like the good frequency response of the PbS cell, is simply the result of its poor sensitivity; for much smaller currents are produced in it than are produced by the same light level in a TF cell.

Variation of Signal and Noise with Cell Area. An elementary consideration[30a] of the output signal and noise voltage from two identical photoconductive cells placed in parallel shows that, because of their mutual shunting effects, the signal must be half that from one cell alone, and the noise less by $\sqrt{2}$. On generalizing to many elements in parallel, evidently the signal varies inversely with the area, the noise inversely with the square root of the area. The S/N ratio thus varies inversely with the square root of the area, just as for photoemissive cells. This holds true regardless of whether the total flux falls on only one cell or is divided between the cells (up to illumination levels where saturation effects begin to appear), since the signal emf's developed in all cells are in phase.

The data shown in Table 1 for various sizes of Cashman cells confirm these predictions within ± 3 db, which is fair agreement considering the variation in layer thickness, sensitization, resistance, and grid spacings. No theory which includes these further variables has as yet been presented. The type B cells show an unexpectedly high signal response for their large area.

Threshold Sensitivity. The threshold sensitivity may be indicated by the hololuminous signal equivalent of noise. For type A cells, as shown in Table 1, this quantity is of the order of 10^{-9} hlm (total swing; square wave, chopped) for the tungsten source with a 2540 filter as in the test set. This corresponds to a threshold sensitivity of the order of 10^{-11} watts (total swing; square wave, chopped) for radiation of wavelengths near 1 μ. Both values depend, of course, on the noise, determined by the bandwidth, which is 1.8 cycles in these measurements. In the voice communication system described in Section 4.4.2, the rms variation of signal which was the equivalent of noise in a type B TF cell was measured under Contract OEMsr-990 to be about 3×10^{-8} effective hlm, the incident signal being from a cesium-vapor source modulated at 1,500 cycles, and the bandwidth being about 600 cycles. The 30-fold difference from the test set threshold values is due principally to the large bandwidth.

Heat Detection. The possible sensitivity of the TF cell as detector of warm military targets was investigated by Contract OEMsr-235, with the results shown in Figure 15. For a target 200 C above background, the TF cell is less sensitive by a factor of 10^3 than an uncooled PbS cell, and by 10^5 than a dry-ice-cooled PbS cell. Because of the shorter long-wave threshold of the TF cell, the slope of its response as a function of target temperature is much steeper than that of the PbS cell, so that the TF cell is relatively much worse for targets closer to the background temperature and becomes comparable to the lead sulfide cell only at target temperatures of 500 C or over.

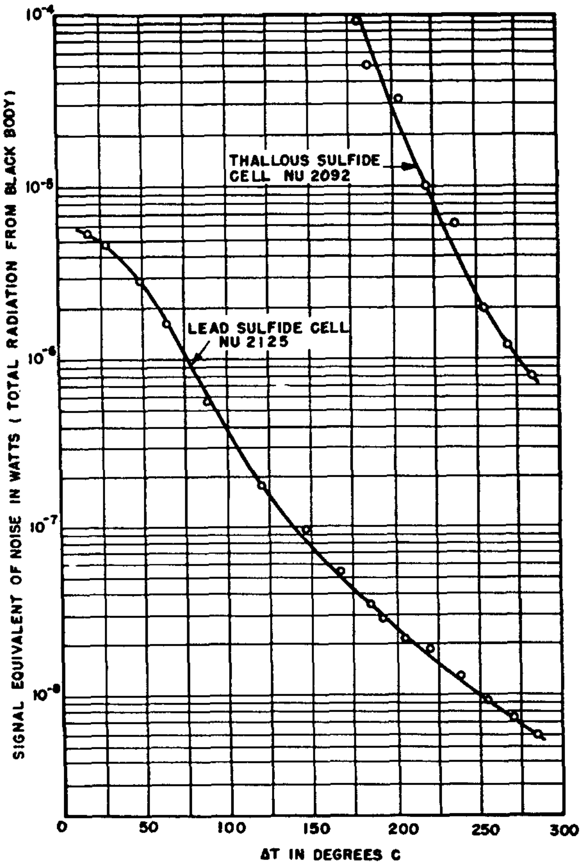


FIGURE 15. Sensitivity of TF and PbS cells at room temperature as thermal detectors.

Secondary Emission. A special cell was constructed under Contract OEMsr-235 containing an electron gun and electrodes for measuring the secondary electron emission of a Tl_2S layer oxidized and unoxidized. This is important because of the possible use of such layers in infrared iconoscopes or other image-forming devices. The voltage of the

incident electrons was varied from 200 to 750 volts. Oxidation and subsequent activation do not produce a marked change in the yield of secondaries. The most favorable yield of 1.35 secondaries per primary electron was obtained over a broad region centered at about 450 volts primary accelerating potential. This yield is too low by a large factor for further consideration in image devices. It would be interesting to determine whether a low secondary yield is characteristic of all sulfides.

Photovoltaic Effects. In the studies carried out in 1941 it was found possible to make very sensitive, but not very stable, low-resistance photoemf thallous sulfide cells by proper oxidation-activation. High-resistance cells showing photovoltaic effects occasionally appeared during the study of photoconductive variables, but they are very rare among the cells made by the final manufacturing processes.

Under Contract OEMsr–235 it was found that the photoemf effects appeared to be associated with large gradients of oxygen concentration in the Tl_2S layer which very likely were altered by oxygen migration, with cell age or under voltage or sunlight, to produce the instability. Such unstable gradients were very undesirable and appeared to be unnecessary for creating photoconductivity; indeed, it was thought that the great improvement in the TF cells introduced by preoxidizing the Tl_2S was due to the increase in uniformity of distribution of the oxygen throughout the finished cell.

Now that better amplifiers for low-resistance devices are available, and more experience in handling Tl_2S has been accumulated, it might be valuable to study the photoemf effects further.

Fundamental and Theoretical Studies

Study of Properties and Interrelations. Extensive and varied studies have been made by all contracts on TF-cell signal and noise and their dependence on some or all of the following factors: cell design; Tl_2S preparation, evaporation, and sensitizing processes; grid spacing and area, cell resistance, and layer thickness; crystal structure and orientation; cell age, and pre-exposure to sunlight and voltage; load resistors and circuit design; signal flux, wavelength, and size of illuminated area; voltage, frequency, bandwidth, steady background light, and cell temperature; and on the interrelations of all these factors.

The factors are very difficult to separate for individual study. Early analysis was qualitative and semi-intuitive, and was aimed primarily at production of better cells by any means, whether fully understood or not. Later, the study of many factors was perforce statistical, relying on large numbers of cells to average out the obvious batch, process, and operator variations. Even for studies which can be made on a single cell, as of variations in the incident flux or in external conditions, few exhaustive studies of all properties were made on the *same* cell even though results are known to differ very much from cell to cell. Many variables have proved to be interdependent in unexpected ways, so that early measurements have been repeatedly invalidated by later results. The pressure for production has of course played its part in slowing down these studies and in making many of them hasty and inconclusive.

As a result, confirmed quantitative relationships are few. They include the relation of signal output to frequency, which was established early;[2] cell resistance as a function of temperature;[3,6,9] and the relationships involved in the steady light saturation effects and in the decay response patterns.[6,9] The variation of noise with frequency was cleared up in 1944 by Contracts NDCrc–185, OEMsr–235, and OEMsr–990.[3,30] The first reliable measurements of output signal linearity as a function of flux level (modulated) over great ranges of intensity were not made until 1945[3] and may still be doubtful at the higher ranges because of possible amplifier overloading. Phase lag needs more study, both theoretical and experimental;[9] likewise the relations between time constant, dark resistance, and degree of oxidation of the Tl_2S layer.[6]

Navy Contract NObs–25392, which is continuing the work of Contract OEMsr–235 at Northwestern University, is apparently providing opportunities for studying background effects under carefully controlled conditions for the first time. As usual with TF cells, this work throws doubt on many earlier results; in this case because background effects are found at very low light levels, possibly comparable with the "darkness" in which earlier experiments were thought to have been conducted.

Theoretical interpretation is in about the same shape. It seems to be agreed, as a result of the MIT work under Contract OEMsr–1036 measurement of thermoelectric effect in TF cells, that the photoeffect is due to "defect" conduction. In this kind of con-

duction the light quantum ejects an electron from a filled conduction band up to a bound or "trapped" state (Figure 16); the conductivity is produced by the mobility of the "hole" left behind in the conduction band.

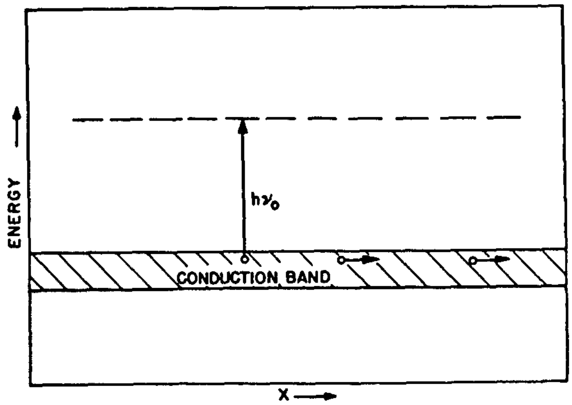


FIGURE 16. Energy state diagram for defect conductor.

Theoretical analysis has been given of the noise-frequency relationship,[28,30b] but the physical mechanism responsible for the relationship is in dispute. Simple interpretations are possible for steady response and time-lag effects. Apparent weak resonance effects at certain frequencies when some background light is present have not been explained.[3,10] Altogether the NDRC literature on TF cells is a mine of exciting material for discussion and a stimulus to further experiment. It should be consulted in the original by the reader interested in the problems of semiconductors and photoconductors.

Assumed Mechanism. The very general results which can be given here will perhaps be better understood and the purpose of some special studies will be clearer if a simple picture of the photoconductive process is outlined first.

A band of low-energy states (Figure 16) in which electrons are free to move throughout the Tl_2S crystal lattice is conceived to be filled completely with electrons at absolute zero temperature, so that no net motion of charge can take place under an applied field and the conductivity is zero. At some distance in energy above the top of this band is a group of trapped electron energy states, probably, according to those working under Contract OEMsr-1036, localized at the oxygen atoms. Into these states electrons may be thermally or optically *excited,* leaving behind a conduction hole which, under the influence of an external electric field, is free to move throughout the lattice by means of the retrograde motion of the electrons surrounding it. Eventually the holes may be neutralized by "collision" with a trapped electron.

The number of these holes per unit volume determines the resistivity of the material. When no radiation is falling on the cell, this number is an exponential function of temperature. When radiation impinges, it increases the conduction if it has an energy per quantum greater than the threshold, $h\nu_0$ or hc/λ_0, which is the minimum difference of energy between the lower and upper states (h is Planck's constant, c is the velocity of light, ν_0 and λ_0 are the threshold frequency and wavelength, respectively). This energy threshold therefore determines both the long-wavelength threshold and the behavior of the resistance with temperature.

This picture of defect conduction was not adopted until after the crucial thermoelectric experiment in 1945. Previously the conduction had been assumed to be of the opposite or "excess" type as described in Mott and Gurney,[33] and the comparison of viewpoints is on this account somewhat confusing. In excess conduction, the trapped electrons are assumed to be *below,* and to be raised to a higher, *empty* conduction band by radiation or heat; the electrons themselves therefore carry the current.

Actually it is now established that both kinds of conduction commonly take place simultaneously (intrinsic conduction) in any real semiconductor, and the effect observed externally depends on their relative proportions under the conditions of the experiment. The early reports based on the excess theory can apparently be converted to the defect theory by a simple change of notation if the conduction is confirmed to be of the latter type.

Variation of Resistance with Temperature. As expected for a semiconductor, the resistance varies strongly with the temperature T, the coefficient being about 6 per cent per degree centigrade near room temperature. Theoretically[32,33] the relation should be

$$R = Ae^{U/kT}.$$

The temperature dependence of the coefficient A is different in different theories but is small and may be neglected. The quantity U is called the "thermal activation energy" and should be equal to $h\nu_0/2$ in

the simple theory just outlined; k is the Boltzmann constant. An experimental plot of log R versus $1/T$ is shown in Figure 11 [3] and obeys this equation very well. The activation energy determined from the slope of the line for the cell shown is 0.47 electron volts. On one good British cell U was found to be 0.43 ev.[9] Under Contract OEMsr–1036 the activation energies of many cells were measured by this method, seeking a relation with the degree of oxidation of the layers, but no relation was apparent, though the change of *resistance* (the constant A) with oxidation was very marked.[6] Values of U varied from 0.41 to 0.77 ev, but it is not clear what range of values are especially characteristic of "good" cells.

The values of U of 0.43 and 0.47 ev correspond, on the simple theory, to optical thresholds of 1.44 and 1.31 μ, agreeing well enough with the photoconductive thresholds commonly observed and with the onset of optical absorption, as far as is known. Obviously, thermal, photoconductive, and absorption studies on the *same* cell are greatly needed.

Response to Steady Flux. The response of TF cells as a function of the total steady flux incident has been measured by all contracts. Large differences are present in the absolute values of response found by different contracts, but these are probably due simply to variations in sensitivity of the cells tested. The general shape of the curves is the same in all cases. The relative change of resistance, $\Delta R/R_d$, has been fitted by those working under Contract NDCrc–185, on the basis of the theory of excess semiconduction, by an equation of the form

$$\frac{\Delta R}{R_d} = \frac{\sqrt{1 + \gamma' P} - 1}{\sqrt{1 + \gamma' P} - C},$$

where γ' and C are constants of the material and P is the radiant power falling on the cell.[9]

This theory was adapted to the point of view of defect or intrinsic conduction by Contract OEMsr–1036, using a slightly different notation. There resulted an equation of essentially identical form which fits the data equally well.[6]

Growth and Decay of Response to a Single Pulse. To throw light on the origin and nature of the time constant observed in the frequency response curves, studies were made under Contract NDCrc–185 with an oscillograph of the growth of response when a steady light is suddenly turned on and of the response to a flash of 10 to 50 μsec duration.[9] Other work by Contract OEMsr–1036 showed the decay of response after a microsecond pulse from a flash lamp.[6]

The simple theory formulated by those working under Contract NDCrc–185 predicted rates of growth of response somewhat different from those observed. It was suggested that the discrepancies were due to "space charge" (polarization) inside the crystal or to the shunting effects of the unilluminated portion of the cell. The predicted effect of pulse length on initial slope of decay was not confirmed. Only the behavior of the decay tail could be taken to agree with theory.

Those working under Contract OEMsr–1036 repeated the studies of response decay with many cells as a function of voltage, light intensity, wavelength, and temperature. They adapted the calculations to their theory of Tl_2S as a defect conductor. Following the microsecond pulse, the response builds up to a peak in about 5×10^{-5} second and then decays. To explain the initial shape of the decay curves, they postulated a distribution of shorter time constants in the material in addition to the dominant time constant τ characterizing the decay tail. The value of τ was found to vary with temperature as exp (U'/kT). The quantity U' was a constant for a given cell and was determined to be 0.65 ev on a cell whose activation energy U was 0.54 ev. The difference between U and U' might be explained by a variation of conduction hole velocity or of capture cross section with temperature.[6]

The value of the time constant τ at room temperature, for a group of cells of the same size, was found to increase with decreasing cell resistance, from 5×10^{-4} second for a 450-megohm cell to 3×10^{-2} second for a 1.6-megohm cell. It appears that the law that τ is proportional to $1/R$ is expected from either theory. Inspection of the data given under Contract OEMsr–1036 on 11 very different cells, scattered throughout the resistance range just given, shows that this law is followed to ±40 per cent. This is surprisingly good agreement, considering the other sources of variation which are neglected in deriving the law. The value of τ seems not to depend on the amount of oxidation, though R does. Perhaps the oxidation accounts for most of the deviations of R from the $1/\tau$ law.

As was expected, τ is found to be independent of the wavelength of the incident light.

Signal and Noise: Frequency Response. The con-

duction electrons must be thought of as continually boiling up from the conduction band and condensing again out of the upper states. The rate of boiling up is constant at constant temperature in the dark. The rate of condensation, which is probably due to neutralization of holes, depends on the number of electrons in the excited state. If an excess boiling rate occurs for an instant, whether from a thermal fluctuation (noise) or because of incident flux (signal), a finite time is required to increase the number of conduction electrons so that equilibrium is restored; if the boiling rate is lowered, again there is a time lag for the conduction to decay.

Because of the lag, whether explainable by this mechanism or by some other, both signal and noise are strongest at low frequencies.

This kind of excitation noise is in addition to the thermal or Johnson noise caused by fluctuations in the number of conduction electrons or holes reaching the electrodes at any instant.[30b] The latter is present in every conductor. It is a function of resistance only and is independent of voltage or frequency for constant bandwidth (white spectrum). The relation between the excitation noise and the Johnson noise is similar to the relation in a triode amplifying tube between noise introduced by the grid and "shot noise." The excitation noise, just like the excitation signal, is amplified by the conduction process in proportion to the drift velocity of the holes, which is proportional to the applied voltage. Because of its time constant, this noise has no high-frequency components and decreases with increase of frequency up to about 3,000 cycles, above which only the Johnson noise remains. This combined noise spectrum closely resembles contact noise, which has been investigated for carbon microphones and thin metallic films.

The linearity of signal and noise with voltage is observed experimentally, except in occasional unexplained cases, up to voltages of 100 to 200 volts where some kind of internal cell breakdown appears to take place, accompanied by large increases in noise. Cells with wide grid spacing, like the type B cell (15 lines per inch), stand voltage better than cells with narrow spacing, as would be expected.

The theoretical expressions for rms signal and noise, as functions of frequency f, when a time constant τ is involved, both take the form

$$\frac{C\tau}{\sqrt{1+(2\pi f\tau)^2}},$$

where C includes the quantum efficiency, electron mobility, voltage, or other parameters.

Since the d-c response ($f = 0$), represented by the numerator, is proportional to the time τ during which conduction electrons can accumulate, it is favored by a long time lag. But with a long lag, the denominator grows rapidly with frequency, and the frequency response is poor. It is observed experimentally that the cells most sensitive to d-c light usually have poor frequency response. The better frequency response of PbS cells as compared with TF cells may be directly connected with their lower sensitivity.

Those working under Contract OEMsr–1036 found that the absolute signal response of any cell measured as a function of frequency on the test set could be predicated by the above expression within 2 db up to 700 cycles, simply from measurements on the d-c response and on the decay curve time constant.

Fluctuations are equalized more quickly—the time constant is shorter—when there are more electrons in the conduction band. This occurs at higher temperatures, or with increased light intensity on the cell. Both conditions are observed experimentally to decrease the sensitivity and to improve the frequency response. However, reliable quantitative measurements are few and are apparently not covered by any simple theory.

Experimentally, the sensitivity of TF cells falls at low temperatures as well as at high, even though the time constants increase with lower temperature as expected. This must mean that the constant C varies with temperature. In some other photoconductors, such a variation has been attributed to changes in quantum efficiency.[32] The possibility of compensating for the poor frequency response at low temperatures, in an aircraft communication problem (Section 4.4.4), by adding background light was considered under Contract OEMsr–990; this proposal deserves testing. Extensive further temperature, background, frequency, and related studies would be very valuable.

Returning to the frequency variation of signal and noise without background at room temperature, it is evident from the expression above that at large frequencies where $f\tau > 1$ both signal and noise (for constant bandwidth) should fall off as $1/f$—or at 6 db per octave—above about 100 cycles. This is observed experimentally for TF cells, as seen in Figure 9, except for occasional unexplained cases in

which the rate is as low as 4 db or as high as 8 db per octave.

Since signal and excitation noise both vary in the same way, the S/N ratio should stay constant up to frequencies where Johnson noise begins to be significant. This also is confirmed by Figure 9 up to about 1,500 cycles, with perhaps as good accuracy as circuit and bandwidth corrections will permit.

Phase Lag. The existence of a time lag in the response of a cell, which leads to the frequency response behavior just discussed, must also lead to phase lags between sinusoidally modulated incident light and the output response. The expression for the lag should be $\tan^{-1} 2\pi f\tau$. The values measured under Contract NDCrc-185 over the range 30 to 800 cycles agree only roughly with this expression.[9] The amount of lag is about right in the middle of the range, the values decrease with background light as τ decreases, but the tangent of the angle is not proportional to frequency as it should be. One explanation for the discrepancy might be experimental difficulties; another might be the space charge and polarization effects not considered in the theory.

Thermoelectric Effect. A special TF cell was constructed under Contract OEMsr-1036, the layer being formed between single metal electrodes without gridwork, with arrangements for heating one electrode and cooling the other by external baths. The direction of the thermoelectric effect was measured. This direction determines whether excess or defect conduction is present. Since the charge carriers will diffuse from the hot junction to the cold junction, the latter becomes charged negatively in excess conduction, positively in defect conduction.

Under Contract OEMsr-1036 it was found that a *pure* Tl_2S layer had excess conduction as in the picture outlined above; but that the sign reversed on oxidation, and the sensitized layer had defect conduction. A layer made from preoxidized material showed defect conduction at all times. Earlier Russian work showed low-resistance Tl_2S to have excess conduction, high-resistance to have defect conduction, but the change of resistance produced by oxidation (in air) was opposite to that observed in all these studies, so it is not positive that the same chemical substance is involved.

The direction of the thermoelectric effect would earlier have been regarded as conclusive proof of the invalidity of the excess conduction theory. But some recent work on other semiconductors indicates that the direction of the Hall effect (transverse voltage developed when a current flows through the material in a magnetic field), which is the only other way to determine the sign on the charge carriers, may give exactly opposite results from the thermoelectric results at a given temperature; and that a study of both effects over a large temperature range is sometimes needed in order to be certain of the interpretations. Such a study would evidently be valuable here.

Crystal Structure. It was expected that some of the photoconductive effects observed, particularly the process of sensitizing with oxygen, would be associated with changes in crystal structure or orientation. Changes of this kind had appeared to be very important in the production of *photovoltaic* cells in the early work under Contract NDCrc-185 in 1941.

Workers under Contract OEMsr-1036 therefore undertook X-ray and electron diffraction studies on the Tl_2S in various stages.[6] X-ray powder pictures were taken of the fused material and of material taken from photocells after various amounts of oxidation. For electron diffraction, photosensitive surfaces were prepared in the diffraction apparatus. Transmission patterns for pure Tl_2S were made with the layer deposited on 0.01-μ thick Formvar films. Grazing incidence measurements were made on layers evaporated on Aquadag coated glass (to prevent charging up of the surface), the layers extending over an adjacent normal cell gridwork for checking the photoconductive properties.

The pure Tl_2S shows the structure reported in the literature. The structure may be thought of as lamellar, the fundamental unit being a triple of Tl-S-Tl layers. Conduction is thought to take place most easily in the Tl planes. In all evaporated layers, these planes were found to be parallel to the backing surface.

In all photosensitive cells, the Tl_2S phase is present; in some cases, a second, yellow, phase is also found. Its structure differs from that of any previously known thallium compounds, but it has been tentatively identified as Tl_2SO_2.

During photosensitization of the Tl_2S layer, the original orientation persists and the crystallites grow in size. However, the diffraction pattern becomes more diffuse and indicates that the structure has probably been disrupted by solid solution of some oxygen. With more complete oxidation only the Tl_2SO_2 patterns appear.

It is supposed that the oxygen first fills in the

interstices between the thallium planes of adjacent triple layers. Complete filling of these holes would require 0.5 mole of O_2 per mole of Tl_2S; photosensitivity is produced with 0.1 to 0.3 moles O_2.

Theories of the Photoconductive Process. From the various experiments on *different* cells, those working under Contract NDCrc-185 were able to compute the orders of magnitude of the fundamental constants entering into their original excess conduction theory. They assumed that the volume of the TF cell layers is about 10^{-5} cubic centimeter and that the quantum efficiency or yield is about 0.1 electron excited per quantum absorbed. The data then lead to a value of the order of 10^{17} for the total number of impurity centers per cubic centimeter from which the electrons are excited. Of these, 10^{14} are unoccupied at absolute zero. The number of conduction electrons present in the dark at room temperature is about 0.5×10^{14}. The mobility of the conduction electrons comes out to be 2 centimeters per second per volt per centimeter. The product of electron velocity times capture cross section is about 10^{-14} cubic centimeter per second, which is small compared to values of this product for other semiconductors.

Those working under Contract OEMsr-1036 concluded that the phenomena would be best explained by defect conduction, with the holes and the electrons in the conduction band migrating in opposite directions under the influence of an applied field, the two having different mobilities. The electrons are much more mobile and cause excess conduction to dominate in pure Tl_2S. In the more sensitive oxidized layer of an active TF cell, the oxygen atoms added during sensitization trap these electrons, leaving the holes to act as the dominant charge carriers.

The action of radiation is considered to be as follows: An electron is raised to an excited state, still bound to its parent atom. In the absence of oxygen, it usually falls back without leaving the atom but not always. Even in pure Tl_2S it will sometimes leave the parent atom and so cause some photosensitivity. This effect, if it is not spurious, is weaker by a factor of over 10^4 than the photoeffect in good cells.[6]

After a cell is oxidized, the picture is different. An excited electron is then likely to jump to a nearby oxygen atom, creating an O^- ion and leaving the positive hole behind which drifts slowly to the cathode. According to this theory, the presence of the hole permits many "secondary" electrons to pass through the material to the anode without being limited by space charge. The number of O^- ions slowly decays as they are neutralized by holes, or, more literally, as the electron on such an ion jumps to a neighboring positive ion which has just been created.

From this theory and the experimental data recorded under Contract OEMsr-1036, the room temperature electron mobility is found to be about 60 centimeters per second per volt per centimeter. Assuming a "primary" quantum yield of about 30 per cent, the hole mobility comes out about 1 centimeter per second per volt per centimeter. The equilibrium density of electrons determined from flash decay experiments is 2×10^{13} per cubic centimeter, from which the activation energy can be independently computed to be 0.51 ev, agreeing with the measured thermal activation energy. The recombination probability (corresponding to velocity times cross section in the excess conduction theory) is 2×10^{-12} cubic centimeter per second; about 40 per cent of the recombination centers decay up to ten times faster than indicated by this figure. From the recombination probability and from estimates of the hole velocity and of the number of holes which collide with oxygen ions without recombining, an oxygen ion cross section of radius 2.5 *A* is indicated, agreeing well enough with known interatomic distances in the lattice.

This theory has not been applied to the noise-frequency problem, but no doubt the Johnson noise would be regarded as mainly electronic, with the excitation noise behavior accounted for by the decay time of the O^- centers.

One advantage of this theory, in addition to its explanation of the thermoelectric results, is that it accounts for the enormous amount of oxygen needed to produce photosensitivity—at least 0.1 mole per mole Tl_2S, or about 10^{22} atoms per cubic centimeter. The function of so much oxygen is not clear by the excess conduction theory, which demands a density of impurity centers only 10^{-5} as great.

The defect theory also will account for the apparent failure of the oxygen to affect the activation energy or the photothreshold or the absorption band of the TF cell layer, which is otherwise hard to understand with these large concentrations of oxygen.

On the other hand, those working under Contract

OEMsr–235 point out that the long-wavelength threshold and the location of the TF-cell absorption bands *have* changed from their wavelengths in the early Case cell, and that this is difficult to explain if the photosensitive material consists only of a solid solution of oxygen in Tl_2S. This group suggests that more careful measurements should be made of the spectral absorption of layers during oxidation, especially at wavelengths longer than 1 μ, in the search for the appearance of new bands possibly arising from new compounds in the layer.

Present Status

The work begun under Contract OEMsr–235 is being continued at Northwestern University under Navy Contract NObs–25392.

Recommendations

No further development work appears to be necessary on the TF cell proper as a military detector of NIR radiation, but the further study of the fundamental properties of such layers, the comparison with other materials, and the working out of more satisfactory theories of the photoconductive process, are all matters of the greatest importance, both scientific and military.

3.3.2 Lead Sulfide Cells

Initial State of the Art

The rectifying properties of galena have been known since 1874. Case, in 1917, seems to have been the first to detect its photoconductive properties,[10] and Lange in 1931 reported its photothreshold as 4.5 μ. The photoproperties of natural PbS crystals vary greatly from sample to sample.

Cashman, in his 1941 semiconductor studies, described in Section 3.3.1, found that PbS could be evaporated in vacuum without decomposition. In 1944, when the NDRC TF-cell development was nearly complete, attention was again turned to Ag_2S, MoS_2, and PbS as possible photodetectors for longer wavelengths, with the results which will now be reported.

This NDRC work was thought at the time to be the first production of photoconductivity in synthetic preparations of PbS, but it was discovered shortly that the Germans had been using PbS cells as IIR and NIR detectors in military equipment for several years.

German Cells. Some of the properties of these cells have been described in a report on the German (Zeiss) Lichtsprecher 250/130 NIR and IIR narrow-beam voice communication system (Section 4.3.1).[14] A number of captured German cells were studied by the University of Michigan under Contract NDCrc–185, by Northwestern University under Contracts OEMsr–235 and OEMsr–990, and by Harvard University under Contract OEMsr–60, as well as by the Naval Research Laboratory.[12,13]

These cells were of two general types. The first, or "button," type consists of a sensitive layer from ½ millimeter square (used in the Lichtsprechers) to 6 millimeters square, without grids. The layer is on a glass backing plate contained in a cylindrical plastic case about 1 inch in diameter and ¼ inch thick, with a small opening in the front, just over the sensitive surface. This opening was covered with a thin glass or quartz window. The cells were made in three series, with plain numbers, numbers prefaced by G, and numbers prefaced by GG. These appear to represent successive levels of excellence attained in a manufacturing program extending over several years.

After capture of the Zeiss works, the process of manufacture of the layers for the small button cells was described.[13] They were made in air, many at one time, by coating a long glass strip, about ⅜ inch wide, with evaporated metal contacts extending the length of each edge. A uniform layer of PbS was deposited along the whole length of the strip. In one process this was done chemically and in another by evaporation. The strip may then have been subjected to further unknown sensitizing operations. Then two more metal strips were evaporated along the edges to improve the contacts. The strip was broken into segments, ¹⁄₁₆ to ⅛ inch wide, each of which formed a complete cell. Contacts were made inside the plastic box by phosphor bronze clips. It was asserted that only one man had the skill required to turn out these cells. Apparently many hundreds of the cells were made during the war.

In the second type of German cell, the Elac (Electroakoustische Gesellschaft), the PbS layer was in the outer bulb of a kind of Dewar flask (as in Figure 17), evaporated over the end of the re-entrant tube in the flask. The re-entrant tube was designed to hold chunks of solid CO_2, pressed against its end by a plunger to keep the layer cold.

The improved response of the PbS cell at low temperatures was also discovered independently under NDRC. These Elac cells were made with sensitive areas up to 1 inch square. The cooled cells were apparently used during the war as heat detectors against ship targets in the English Channel. Work had also been done on their use as the sensitive elements in proximity fuzes. A few cells of somewhat similar type but with inferior characteristics were apparently produced also by Allgemeine Elektrische Gesellschaft.

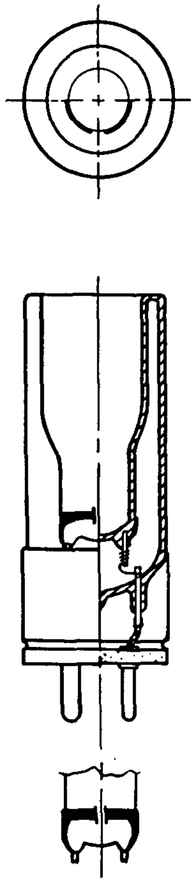


FIGURE 17. Diagram of re-entrant PbS cell.

The fundamental properties of the German cells seem to be similar to those of the NDRC PbS cells, but the recent samples of the latter appear to be more stable and much more sensitive. The long-wavelength thresholds of both appear to lie at about 3.6 μ, and a factor of 10 to 100 in sensitivity is gained in both by going to dry-ice temperature.[12]

British Cells. Before the end of the war a few British PbS cells had been made, following NDRC and German methods and designs. A few of these also came to this country for testing.

No other foreign PbS-cell manufacture is at present known.

Course of Development

History of Development. The PbS-cell program in this country during the war developed late and was sponsored only by NDRC. Although various branches of the Services showed great interest in the work, no formal Service project requests had been set up before the end of the war.

Because the discovery of the cell is so recent, its great promise as an NIR and IIR detector has not yet been fully explored.

The PbS cell was developed by Northwestern University under Contract OEMsr-235. Following the successful development of the TF cell, attention had been turned in February 1944 to possible selective photodetectors of longer wavelengths. Crystals and evaporated layers of several materials were studied without much success until the fall of 1944, when it was found that oxygen photosensitizes lead sulfide. The sensitivity of the first PbS cells made was very low, but by December 1944 it had been brought up enough for accurate measurements of response characteristics. At that time, two captured German PbS cells were received and studied.

In 1945, further increases of sensitivity were obtained, until the uncooled PbS cells finally had S/N ratios on the test set only 10 to 20 db less than the ratios for TF cells of the same area. With the lead sulfide, moreover, cells could be made in sizes down to less than 1 square millimeter. These consequently had S/N ratios about equal to the ratios of the smallest good TF cells (about ¼ inch square) when measured on the test set with a filter.

The PbS cells have a remarkable combination of characteristics: photoresponse to long wavelengths, good frequency response, and a very high sensitivity compared to thermal detectors such as bolometers. This combination made possible the use of a new region, the IIR, both for purposes of voice communication and for purposes of heat detection.

To explore this region, atmospheric transmission measurements in the IIR were undertaken in 1945 by Harvard University Contract OEMsr-60 (Section 4.8 and Chapter 9). Studies preliminary to the

development of IIR voice communication systems were begun by Northwestern University Contract OEMsr–990 (Section 4.8). A device using PbS cells for the detection of heat radiation from military targets such as men and ships was built and tested by University of Michigan Contract NDCrc–185 (Chapter 9).[11]

Military Importance: The Intermediate Infrared. The *intermediate infrared* [IIR], in which the PbS cell is the first photosensitive detector, is taken to extend from the NIR limit at 1.4 μ set by the TF-cell threshold to the great atmospheric water-vapor absorption band at 6 μ. There is promise that other sensitive photodetectors may shortly become available which will have thresholds much closer to the 6-μ limit than does the present PbS cell.

The IIR has two advantages over the NIR as a channel for voice and code communication and recognition systems. The first lies in the comparatively great security of IIR sources at present, since, when properly filtered, they can be detected only by the PbS or some other long-wavelength cell. Such sources can be made almost impossible to detect by NIR-sensitive devices, which are now and will undoubtedly remain for many years many times more numerous and more varied in their modes of operation than IIR detecting devices.

The second advantage is the better haze and fog penetration by the IIR. An IIR communication or recognition system of average power has no greater range than the same type of system adapted for the NIR, but because of the curious behavior of the water-vapor bands responsible for the IIR attenuation (Section 4.8), the range is less affected by hazy weather. Also a given *increment* of power increase produces more effect on range than in the NIR. Incidentally, the better frequency response of the PbS cell may make possible new approaches to the communication problem by the IIR which are not possible with the more sluggish TF cell operating in the NIR.

The second great military use of the IIR is in heat detection. For military targets only a few degrees above the background temperature, the peak of the differential heat emission occurs near 10 μ. Such targets may be detected with thermal detectors (Chapter 8) sensitive in the far infrared, between the water-vapor and carbon-dioxide bands at 8 and 13 μ. But there is still appreciable emission by such targets in the IIR. With a detector such as the cooled PbS cell, which seems to be over 100 times more responsive in its wavelength range than conventional bolometers, a target only a few degrees above background may still be detected, in spite of the limitation of the cell response to wavelengths less than 3.6 μ. Indeed, the first PbS-cell heat-detection system was able to pick up a certain ship target at about half the limit range of a well-developed thermal detector[11] (Chapter 9). For a new type of cell in the first apparatus built, this seems extremely promising. The German application of the cell in this manner is further proof of its potentialities.

A great advantage of the PbS cell in this comparison is its speed of response, the time constants being of the order of 10^{-4} second compared to 2×10^{-3} second for the best thermal detectors developed by NDRC during the war. The percentage of atmospheric transmission over a path length of several miles averaged over a wide band of wavelengths in the IIR is no less, and may be greater, than in the FIR (Section 4.8).

Description of Cells Developed

Cell Types and Construction. Two main types of PbS cells were developed under Contract OEMsr–235.[10] The first is similar to the TF cell type shown in Figure 6, with the evaporated PbS layer placed on the bulb wall. The need for grid-shaped contacts is not so great as with TF cells since the resistivity of lead sulfide is less than that of thallous sulfide. Some PbS cells were made with grids, some simply between linear contacts. The grids or lines are ruled, like those in the TF cells, with Aquadag.

The second type of PbS cell is like that shown in Figure 17. A re-entrant inner chamber permits cooling of the sensitive evaporated layer which is on the outside wall of this chamber. The leads are brought out from the bottom to minimize the problem of current leakage due to condensed water vapor between the leads. A variant of this design was used for some cells which were made by chemical deposition of the PbS instead of evaporation.

Various sizes of sensitive area have been made with good success from about 0.5 square millimeter to about 2 square inches.

The cell envelopes are Nonex glass, though quartz would withstand high evaporating temperatures better and would give better transmission near the long-wavelength limit of the cell response beyond

3 μ, if it could be adapted to easy manufacture. Soft glass can be used for chemically deposited cells.

The construction and cleaning of the glass components follow the lines already described for the TF cell in Section 3.3.1.

The chemically deposited lead sulfide layers were made by Brückmann's method from a reaction between lead acetate, thiourea, and sodium hydroxide. This material had the same long-wavelength threshold and the same good filter transmission and frequency response as the evaporated PbS cells, but it never gave as high or uniform sensitivity as the latter, although attempts were made to activate it by several different methods.

The lead sulfide used for the evaporated layers is made by precipitation with H_2S from a solution of lead nitrate in distilled water. The black precipitate is dried in a vacuum desiccator and then removed and fused in vacuum, like the Tl_2S for TF cells. The crystalline PbS is then crushed to a fine powder and stored in evacuated ampoules for future use.

The evaporation procedure is similar to that for TF cells. About 10 milligrams of the PbS powder are required for the usual cell sizes. The condensation is directed to the proper part of the cell wall by suitably located external heaters and air blasts in addition to the gas flame used for the evaporation. The evaporation is carried out in the presence of about 200 microns pressure of air flowing continuously through the cell to sweep out SO_2 formed by reduction of some of the PbS. After the layer has been formed it is baked for 10 minutes at about 400 C in an oven, then cooled to room temperature and the air flow stopped. Pumping continues for 10 to 30 minutes during which the resistance increases to an apparently stable value. The cell is then sealed off.

Summary of Characteristics. Some of the PbS cell characteristics are summarized in Table 1. The values are only rough indications of the cell possibilities, as they are based on only a very few cells constructed in an initial stage of the development.

An attempt is made to keep the cell resistance in the range from 0.5 to 20 megohms for the same reasons as given for the TF cell. Since the resistance increases by a factor of 10 to 100 on going to dry-ice temperature, cells which are to be cooled are made to have very low resistance, 0.2 megohm or less, at room temperatures. The temperature coefficient of resistance of the PbS cell is about 2 per cent per degree centigrade. This is about one-third that of the TF cell, as expected from the three times longer wavelength threshold (see "Variation of Resistance with Temperature," Section 3.3.1). No consistent and detailed measurements of the change with temperature over a large range are yet available for computing the thermal activation energy of the PbS cell.

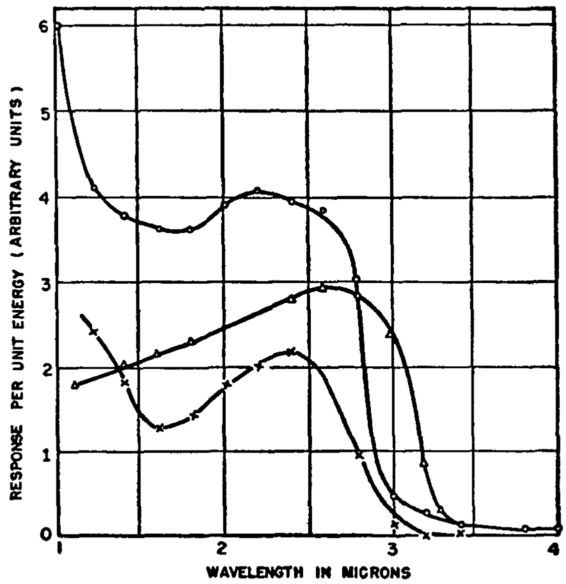


FIGURE 18. Spectral response curves of some PbS cells.

The spectral response curves of three PbS cells are shown in Figure 18. They were measured under Contract OEMsr–235 on a Bellingham and Stanley single-prism rock-salt monochromator.[10] The long-wavelength tail response shapes are uncertain because of the large spectral slit widths required in the instrument at these wavelengths. For accurate threshold measurements, a doubly dispersing monochromator would be needed. The threshold is at approximately 3.6 μ just as in the German PbS cells. The peak near 2.5 μ in each of the curves is believed to be characteristic of lead sulfide. The peak indicated near 1 μ seems to have an intensity proportional to the amount of oxygen taken up by the cell. The response at wavelengths longer than 1 μ depends greatly on the thickness of the layer used, for the material becomes almost transparent as the threshold is approached. Unfortunately the thicker layers are hard to sensitize, and the best surfaces seem to be slightly transparent even in the visible region. The spectral response has been measured to

wavelengths shorter than 0.5 μ with a Van Cittert glass double monochromator, and it is believed to continue to a short-wave limit imposed by the absorption of the cell wall material.

There are indications that the spectral response curve is not quite the same for cooled and uncooled cells. More careful measurements on this point are needed.

The usefulness of the PbS cell in IIR communication and signaling devices depends not only on its spectral response curves but also on the transmission of the atmosphere and optical materials and on the sources used. These factors are discussed in Section 4.8.

At room temperature the S/N ratio of PbS cells made in 1945, as measured on the test set, is some 20 to 30 db below that of a TF cell with a sensitive area of the same size if the tungsten light source is unfiltered in both cases. The Corning 2540 filter reduces the TF response some 15 db, the PbS response about 5 db, leaving the PbS cell with a ratio 10 to 20 db below that of the TF cell for the filtered source. [If the source were at 1500 K instead of near 3000 K, these relations would be completely altered (see Section 4.8).]

For the test set source filtered in this way, the hololuminous threshold signal of two different sizes of PbS cell is shown in Table 1. With such a source and filter, the total energy that lies in the wavelength region of PbS response is about 7 times as great as that in the region of TF response. Thus, the S/N ratio, *per unit incident energy* near the wavelength of peak response of each cell, is perhaps 25 to 35 db lower for the PbS cell than for the TF cell. This estimate is confirmed by the comparative response of the two types of cells to a monochromatic source, such as the cesium-vapor lamp.

When the PbS cell is cooled and the load resistor in the circuit properly matched at every temperature, in the usual circuits the noise stays about constant, but the signal strongly increases. At dry-ice temperature, the improvement in S/N ratio may amount to 20 or 30 db; at liquid-air temperature, several decibels more.

Within statistical uncertainty on the few cells made, the S/N ratio of the PbS cells is inversely proportional to the square root of the area just as expected theoretically for such detectors and as already confirmed experimentally for TF cells.

The absolute values of both signal and noise of the PbS cells are very low compared to TF cells of the same size (Table 1) and therefore impose exacting requirements on amplifier design if the ultimate sensitivity is to be reached. The best designs seem to be similar to those of TF-cell amplifiers, with careful selection of components to minimize noise.

The signal and a large part of the noise are proportional to applied voltage, as with the TF cell. But even at low frequencies voltages over 45 are generally required before the voltage-dependent part of the noise becomes larger than the Johnson noise. Careful studies have been made under Contract OEMsr–235 on the variation of noise with voltage.[10]

The equations developed for the variation of signal and noise with frequency for TF cells also apply here in first approximation (Figures 19, 20, and 21)

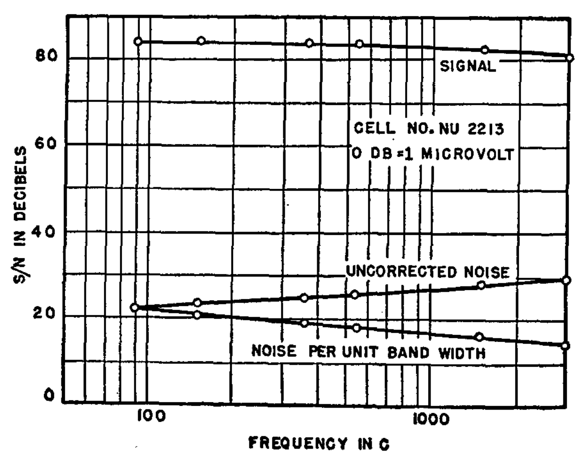


FIGURE 19. PbS cell signal and noise versus frequency at room temperature.

but with time constants substantially shorter. The τ's for PbS cells are about 10^{-4} second at room temperature and 5×10^{-3} second at dry-ice temperature, compared to about 10^{-2} second for a TF cell at room temperature. As a result of these shorter time constants, the signal response of some PbS cells may be down as little as 5 db at 20,000 cycles compared with its value at 30 cycles.

A more exact theory of signal and noise will be needed in order to explain the resonance-type peak at 1,500 cycles in the lower corrected S/N curve shown in Figure 21. Similar peaks occur at other frequencies in TF cells exposed to steady background light. It is just possible that they may be due to the amplifying circuits and not to the cells, although

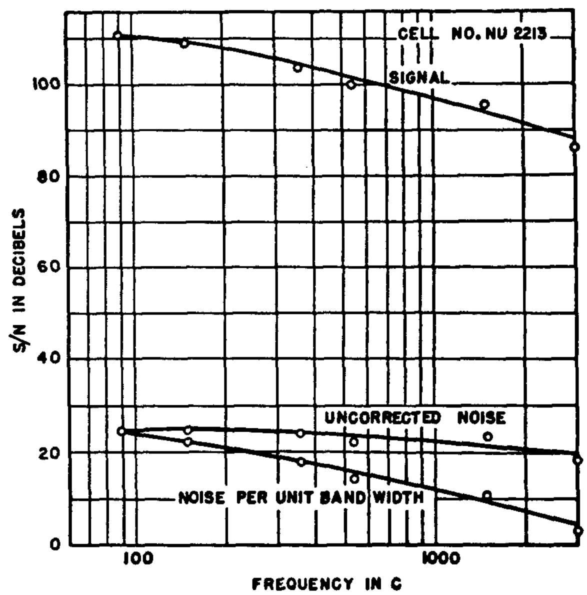


FIGURE 20. PbS cell signal and noise versus frequency at −80 C.

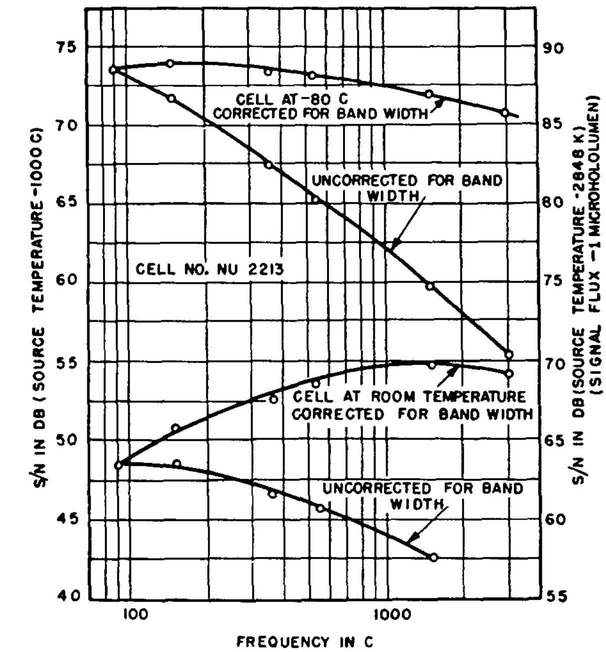


FIGURE 21. PbS cell S/N ratios at room temperature and at −80 C.

great precautions were taken to get true cell characteristics in these measurements.

Present PbS cells may be operated in direct sunlight with only 1 to 4 db loss in S/N ratio. The response is linear with incident flux, from the noise level up to a flux of about 0.01 hlm, corresponding to 30 or 40 footcandles of tungsten lamp illumination. The linearity thus extends over a range of almost 10^7 in incident flux level. The comments made for TF cells on the origin of the nonlinearity also apply here.

It seems likely that the short time constants and better frequency response, the 10- to 100-fold increase in the range of linearity of the PbS cell, and its 10- to 100-fold smaller sensitivity to background light, compared to the TF cell, are all intimately associated with its 10- to 100-fold smaller responsivity per unit energy (at room temperature) than the latter cell. An insensitive cell in general has these otherwise favorable characteristics, as discussed under "Fundamental and Theoretical Studies," Section 3.3.1. If this is the explanation here, then any success in increasing the responsivity of the PbS cell will be offset somewhat by poorer performance in these respects.

It is possible also that increased responsivity may not be possible, the attainable S/N ratio of long-wavelength detectors perhaps being inherently lower than that of short. This is one of a number of basic limitations, independent of specific cell material or postulated mechanism, which are suggested by various aspects of the behavior, both absolute and comparative, of TF and PbS cells and other selective photodetectors. Such theoretical relations, if they exist, seem not to have been developed or set down anywhere explicitly as yet. They would probably run parallel to the similar S/N ratio and temperature relations which are already well established for nonselective thermal detectors.

Heat Detection. The sensitivity of a TF cell and of a PbS cell, cooled and uncooled, to targets at temperatures of a few degrees above background, is shown in Figures 15 and 22. The ordinate in these graphs is the total incident energy, integrated over all wavelengths, from a black body, which must fall on the cell in order to produce threshold response. The response behavior as shown by these graphs differs from that of thermal detectors. The PbS cell sensitivity increases steeply with increasing temperature of the black body above its surroundings because higher temperature radiators are richer in the shorter wavelengths to which the PbS cell is more sensitive. For ordinary nonselective thermal detectors, the sensitivity *per unit integrated energy* is almost independent of the black-body temperature.

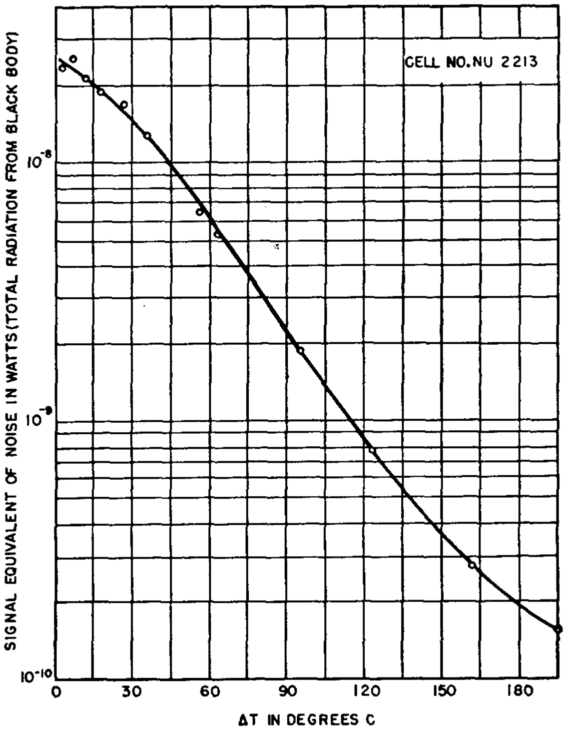


FIGURE 22. Sensitivity of PbS cell at −80 C as a thermal detector.

If the temperature of the body is within a few degrees of that of the surroundings, it can be proved[10] that the response per unit energy for the PbS cell also becomes independent of the body's temperature and is determined only by the spectral response curve in the last few tenths of a micron near the long-wavelength threshold, as shown in Figure 23. The curves of Figures 15 and 22 must thus become horizontal at the point where they intersect the vertical axis. This point was at about 5×10^{-6} watt for one cell with a ¼x¼-inch sensitive area with 5-cycle bandwidth (Figure 15). It is at 3×10^{-7} watt for another cell with a 1x1-inch sensitive area at room temperature. For the latter cell at −80 C (Figure 22), it becomes about 3×10^{-8} watt. This is equal to the response of thermal detectors, within a small factor, as proved by the tests on the equipment described in Chapter 8.[11] For sources, such as unshielded motor exhausts, which are more than about 60 degrees above the background the cooled small PbS cell will evidently become much more sensitive than the thermal detectors.

For motor exhausts, indeed, the PbS cell might be a uniquely sensitive detector because much of the radiation from them is said to be concentrated in gaseous molecular emission bands, some of which fall in the region of greatest sensitivity of this cell. The problem and possible success of this kind of detection, coupled with the important related problem of transmission of the radiation through the atmospheric water-vapor and CO_2 absorption bands, needs a great deal of careful study and has scarcely been touched to date.

Cells for heat detection should be made in quartz because of the poor transmission of Nonex and most other glasses in the important PbS threshold region, where the overall detection curve reaches a maximum, as shown in Figure 23.

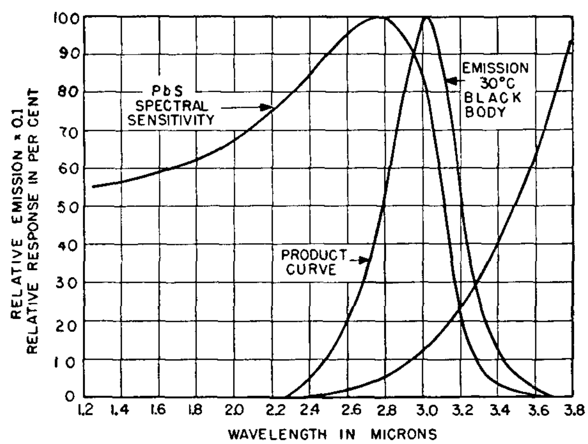


FIGURE 23. Effective wavelength region of PbS cell sensitivity to black-body radiation.

STUDY OF VARIABLES

Some samples of galena were found pure enough to give satisfactory results in the evaporation method. However, since the percentage of impurity is widely variable from one sample to another, galena is not recommended for production purposes.

The lead sulfide layers prepared by chemical deposition exhibited slight photoconductivity, which improved greatly on cooling the layer. It also improved if the layer was subjected to heat treatment in a vacuum for up to 5 hours at temperatures near 150 C. No improvement was obtained by heat-treating in oxygen.

The heat treatment in vacuum increased the resistance and the S/N ratio each about 100 times. If the heat treatment was carried to temperatures above 170 C, the layer lost its photosensitivity permanently, and the color changed from the blue-gray of PbS to a dull brown. Further heat-treating in air or oxygen or in vacuum at temperatures up to 500 C failed to restore the photoconductivity.

The chemically deposited layers could also be made very photosensitive by alternate heating and cooling, using a gas-air flame in direct contact with the layer; the brown color did not appear in this case.

The loss of sensitivity on slow heating to above 170 C was thought by those working under Contract OEMsr–235 to be due to the appearance of decomposition products of oxides or organic compounds which might have been present in small quantities in the layer. Perhaps the sudden heating is successful because it drives out such impurities before decomposition can occur.

Oxidation is carried on during the evaporation. The air is flowed through the cell continuously rather than allowed to stagnate because there are indications that decomposition and reduction of PbS accompany the oxidation at least above 400 C, with formation of S and SO_2 vapor. It is necessary to sweep out these vapor products, as it appears that SO_2 poisons the sensitization, possibly by combining with the sulfide.

The rate of the increase of resistance which occurs after the cells are cool, during the final pumping prior to sealing off, is thought to indicate the presence of vapors not removed by the pump, which are entering into a surface reaction with the layer. These vapors might be water or sulfur, but the exact reactions are unknown.

Water vapor proved very important in the oxidation of the TF cells to insure stability and low resistance. It is much less important here because both properties are easily obtained using dry oxygen in the sensitization. However, the activation of the PbS may be carried out at lower temperatures when water vapor is present. This is considered desirable because the PbS is rather strongly reduced at higher temperatures, and hence water vapor is customarily used in the cell manufacture.

Almost no fundamental and theoretical studies have been carried out on the PbS cell and the mechanism of its photosensitization. Nevertheless, the similarities between its behavior and that of the TF cell are so great as to provoke reflection at every point and to suggest that both must be encompassed by the same theory and the same mechanism. Perhaps other sulfides, such as the Ag_2S and the Mo_2S already studied, may be made into successful cells with similar characteristics if further work is carried out on them. Other compounds, particularly the selenides and tellurides, also need study. Selective detectors sensitive to still longer wavelengths may be found by such investigation.

Present Status

The work begun under Contract OEMsr–235 is being continued at Northwestern University under Navy Contract NObs–25392, with particular emphasis on the investigation, fundamental study, and development of PbS cells and other IIR detectors.

Recommendations

The study and development of PbS cells can and should be brought up to and beyond the level attained with TF cells. Possibly the S/N ratios can be increased further. Those working under Contract OEMsr–235 have recommended more study of the effect of cooling chemically deposited PbS layers. More accurate spectral response data are needed, as well as measurements on signal and noise above 20,000 cycles (for possible use in multichannel systems).

The field of IIR detectors and military systems seems wide open for further exploration and for theoretical analysis. Since the importance of this field is appreciated by the Armed Services and work is going forward in this direction, no further recommendations need be made.

3.3.3 Silicon Cells

Course of Development

Work had been under way at the Bell Telephone Laboratories for some time on the preparation of semiconducting layers by the decomposition, at heated solid surfaces, or chlorides, hydrides, and other volatile compounds of certain elements. In 1943, G. K. Teal and J. R. Fisher discovered that some silicon samples, prepared in this way by decomposing $SiCl_4$, were photosensitive.

Several small rod-shaped samples were tested by the University of Michigan Contract NDCrc–185, and proved so promising as infrared detectors that Contract OEMsr–1231 was set up in October 1943 at Bell Laboratories with the principal object of extending these techniques to the production of silicon cells of larger size.[15,16]

Under this contract over 100 cells, each of an area of about 2 square inches, were made on porcelain or quartz backing plates and tested at Bell Laboratories and at the University of Michigan to ascer-

tain the effect of variables in the manufacturing process and to determine the order of magnitude of attainable responsivities. The cells compared favorably with TF cells in relative infrared response, in frequency response, and in their insensitivity to background light, but the attainable S/N ratios of the best cells, as measured on the photocell test set, were 30 to 50 db lower than those of average TF cells.

It was concluded that the preparation of silicon cells which would be as successful for infrared detection as TF cells might not be impossible, but that it would require a long-time research program to accomplish. Because of the meager promise of success in a short time, Contract OEMsr–1231 was terminated in March 1944.

Construction of Cells

The cells were constructed by placing the porcelain or quartz plates in a vacuum furnace through which $SiCl_4$ vapor was carried by a current of hydrogen gas. In the early experiments with small cells, only the cylindrical cell itself was heated by direct means, but to produce uniform large cells it was deemed necessary to heat the cell base disks indirectly in a furnace. It is believed that this may have introduced into the process an element of uncertainty about the exact effective temperature, pressure, and concentration of the reacting vapor.

The $SiCl_4$ vapor was obtained by passing H_2 gas through a reflux condenser over a boiling flask of the liquid. This vapor mixture was diluted as desired by additional H_2 gas. In the studies, the $SiCl_4$ concentration reaching the furnace was varied over wide limits, though the absolute concentration was indeterminate because of the effect of the heated furnace walls. The temperature of the furnace and cell during deposition was varied from 1017 to 1225 C, and the time of deposition from 3 to 120 minutes, the best results being obtained at about 1030 C and 20 minutes.

The most sensitive films were not the most uniform in appearance but were discolored with brown patches down the center of the plate.

General Properties

Only films with fairly high resistances—from 1 to 20 megohms—were highly sensitive.

The spectral response curve of these cells has a peak near 0.8500 μ and a threshold between 1.2 and 1.4 μ.[15] The ehT° values of various NIR filters with respect to these cells are usually equal to or a few per cent greater than the ehT° values with respect to TF cells.

The noise levels for the Si cells as measured on the photocell test set were comparable with those of type A TF cells, but the signal response was 30 to 50 db lower. Consequently, the signal equivalent of noise was very large—about 0.1 microhololumen at 90 cycles, with bandwidth 1.8 cycles, compared to about 10^{-3} microhololumen for a TF cell. The response over a single Si cell surface was very nonuniform.

In spite of this unfavorable comparison, the responsivity of the small Si cells is reported to be equal to that of a selenium bridge photocell, and their stability and speed of response far better.[16]

Signal and, presumably, noise vary with frequency in the same way as with TF cells (see Section 3.3.1), but with much shorter time constants—about 3×10^{-4} second, compared to about 10^{-2} second for TF cells. The signal response is thus down only 6 db at about 700 cycles. No careful measurements of the variation of noise with frequency have been reported.

The response of the Si cell to modulated radiation is decreased less by steady background masking flux than is the response of a TF cell. The Si cell response decreases by a factor of 4 under background illumination of 500 footcandles, while TF-cell response may decrease by a factor of 100 or more under the same conditions, depending on circuit adjustments.

Very likely the short time constants and the insensitivity to background light are associated with an exceptional linearity of response, but this has not yet been reported; and all these properties are possibly bound up with the low responsivity just as was conjectured to be the case with PbS cells.

The variation of resistance with temperature has been explained [16] in terms of three different apparent activation energies, one near 0 ev at low temperatures, another between 0.3 and 0.8 ev at temperatures from 200 to 500 C, and another of 1.12 ev at high temperatures. It has been assumed that "the value 1.12 ev represents the separation of the conducting and nonconducting bands in silicon." [16] The Si films completely absorb radiation out to about 1.05 μ and become somewhat transparent at longer wavelengths. It is concluded that the same electron bands are concerned in the photoelectric, optical, and thermal processes; a similar

conclusion has already been reported in Section 3.3.1 for TF cells.

It was found under Contract OEMsr–1231 that the quality of Si cells produced was quite erratic, even when the conditions of deposition were controlled as carefully as possible, and that some unidentified variable must be present. It seems at least possible, judging from the similar early results with TF and PbS cells, that the variable may be oxidation. It is to be regretted that no direct attempts were made to photosensitize the Si films with oxygen, or oxygen and water vapor, or by some other method, following deposition. Perhaps this omission may be attributed in part to wartime security barriers to the free exchange of ideas and information. Since the Si films behave so nearly like the TF and PbS films in other respects, they may behave alike in this.

It would seem to be worth while to continue the work with Si cells for the sake of the light they can throw on the nature of the photoconductive process.

PRESENT STATUS

Contract OEMsr–1231 was terminated in March 1944. Some work on Si cells seems to be continuing at Bell Laboratories.[16]

RECOMMENDATIONS

These cells need more study for the comparison of their photoconductive mechanisms with those of TF and PbS cells.

3.3.4 Selenium Electrolytic Cells

Early in the war a quite different type of photoconductive cell, a selenium electrolytic photocell, was developed by the Massachusetts Institute of Technology under Contract OEMsr-561[18,19,20] but without any very valuable military results. This contract was set up under Section D–3 in July 1942, and only the last few months of the contract, up to June 1943, were under Section 16.4. The cell is not especially suited for infrared work as it has a spectral response curve similar to that of the selenium barrier-layer cells in common use in footcandle meters and exposure meters with the peak response at about 5500 A and the long-wavelength threshold near 9000 A. Therefore only a brief description will be given here.

The cell usually consists of platinum electrodes completely electroplated with metallic selenium and immersed in selenious acid. No gases are evolved and the acid renews itself during cell operation so that the cell can be hermetically sealed. With an external d-c potential of 2 to 4 volts across the cell, the cell resistance is found to vary with light incident on the cathode. Load resistors of only a few thousand ohms are used or else equivalent feedback circuits.

The cell has a short-circuit sensitivity of about 1,000 μa per lumen with 2 volts applied, and a dark current after initial seasoning of about 1 μa, with noise about 10^{-3} μa measured on a sensitive galvanometer. The signal equivalent of noise is thus, at best, about 1 μlm for light either unmodulated or modulated at 90 cycles. This is at least 1,000 times less sensitive than a TF cell, for example.

After termination of the contract, some of the personnel and facilities were taken over by MIT Contract OEMsr–1036 which was set up at that time to study the fundamental properties of TF cells (Section 3.3.1). No further military development of this selenium cell was considered warranted.

3.4 Summary of Recommendations

Continuation by the Armed Services of the development and production of photoconductive cells, especially TF, PbS, and related types for the IIR, is a "must" item for any infrared communication, signaling, and detection program. These cells are of the greatest military importance for ship, plane, or personnel detectors; for tracking, guiding, and heat-homing systems; for proximity fuzes, and for voice and code secret IR communication and signaling.

Photovoltaic cells for the NIR and IIR need further study.

Commercial production and development of photoemissive devices will probably take care of most needs of the Services in that line, so that the intensively sponsored development will be needed only to meet the specialized requirements of particular applications. However, the design and fabrication of high-quality photomultiplier tubes for large-scale use is a rather specialized process for which the maintenance of small, constant pilot production may be advantageous if future military applications of such devices are likely to be extensive.

Chapter 4

NEAR INFRARED VOICE-CODE COMMUNICATION SYSTEMS

By *John R. Platt* [a]

4.1 INTRODUCTION

4.1.1 Object and Scope of Chapter

ONE OF THE principal military uses for the *near infrared* [NIR], 0.8 to 1.4 μ, sources, filters, and photodetectors described in Chapters 1, 2, and 3 is their assembly into complete systems for voice and code communication on an invisible "beam of light." Such systems are commonly called photophones, optical telephones, or the like. Voice systems based on several different principles were developed under NDRC auspices and will be described in this chapter. A few of these systems include provision for code operation. Systems which transmit code only will be taken up in the next chapter.

The voice systems cover a considerable range of sizes and military applications. A hand-held system (type W) weighs 25 pounds, has a beam angle of 5 degrees and an *average clear weather* [ACW] night range of 3 miles (see Sections 4.3.2 and 4.3.1). A system for aircraft weighs 60 pounds, has a beam angle of 15 degrees, and an ACW range of 4.5 miles (Section 4.4.3). A shipboard installation (type E) weighs 200 pounds, has a beam angle of 15 degrees, and an ACW voice range of 6.5 nautical miles but a code range of 9 nautical miles. In these systems the intensity of the light beam is modulated at audio frequencies. As it was feared that after a time such systems might be in danger of being received by enemy infrared receivers occasionally, work was also undertaken on devices which could offer still more security. One such device made use of high-frequency carrier waves and one used modulated polarization of the light beam. Another which has been considered would produce modulation by varying the wavelengths used for the communication.

Comparative mention will also be made of foreign and of American NIR voice systems which were not developed under NDRC auspices.

Estimates will be given of the expected performance of similar systems in the *intermediate infrared* [IIR], 1.4 to 6 μ, which would at present have somewhat more military security.

[a] Northwestern University, Evanston, Ill. Now at University of Chicago, Chicago, Ill.

4.1.2 Communication by Means of Near Infrared Radiation

ADVANTAGES OF THE NEAR INFRARED REGION

In principle, radiation of any wavelength region throughout the electromagnetic spectrum may be used for conveying energy in communication. Radio wavelengths are, of course, excellent for most uses, but for some military purposes they may have a dangerously great communication range and are subject to skip-distance phenomena and reception out of the line of sight even when ultrahigh frequencies are used in directed beams. For increased secrecy in combat communication it becomes desirable to go to still shorter wavelengths for which the beam can be sharply defined and the range definitely limited by the horizon or by atmospheric attenuation.[30]

At wavelengths shorter than the radar microwave region, radiation is not detected by tuned receivers but by thermoelectric elements in the region of long heat waves and by photoelectric detectors in the IIR region and at shorter wavelengths. Of these two types of detectors only the photoelectric devices have response times short enough to be used for receiving the audio-frequency variations in voice communication, and such communication is thus limited at present to wavelengths below 6 μ.

Optical communication systems require much higher powered transmitters than radio systems to obtain the same range for the same beam spread, even when atmospheric attenuation is neglected. This is partly because the effective "antenna" areas of practical photodetectors are much smaller than for radio; and partly because, even for equal received energy, photodetectors are less sensitive. This is because of the higher quantum energy required at optical frequencies to eject a photoelectron as compared with the quantum energy required at radio

frequencies to set an electron in motion in an antenna. A narrow-angle optical system may, however, compare in range with a nondirectional radio system of the same power.

Sensitive photodetectors for the IIR region, from 6 to 1.4 μ, have been developed quite recently, and most work up to the present has been done in the NIR region, from 1.4 to 0.8 μ. In the visible region, between 0.8 and 0.35 μ, optical systems are limited to daylight use where a flash of light will not jeopardize security. Even in the *ultraviolet* [UV], below 0.35 μ, night use is risky, because although the UV radiation itself cannot be seen at night it will produce a strong and very visible fluorescence. In addition, as the UV is approached, atmospheric attenuation becomes serious. The development by the NDRC of UV systems is reported in the Summary Technical Report of Division 16, Volume 4, Chapter 6.

Considering these limitations on other spectral regions and the present American and foreign military interest in the NIR and IIR regions for various purposes, it seems likely that systems using these wavelengths will become increasingly important in future military short-range communication (under 10 miles), for instance between tanks, advanced infantry, and ships and planes in convoy or formation. One drawback of such systems at present is their loss of range in daylight, but recent photodetector developments promise great improvement in this respect.

Types of Military Applications

Almost all earlier NIR systems used *very narrow beams* (under 1 degree) for high security. These required fixed stations and tripod mounts and were unsuited to a mobile war. *Wide-angle systems,* with beams between 5 and 30 degrees, and even *all-around systems* with beams over 100 degrees wide give an intermediate security which still is much greater than that of radio. They can be hand-guided or in some cases need not be guided at all.

The military characteristics required in the project control numbers of the developments to be reported show rather well the most urgent military problems for which such NIR systems were desired. All these problems involve communication between mobile positions or moving units at short ranges, under conditions requiring radio and radar silence.

It may be noted in this connection that the use of the NIR system as a link between telephone lines across breaks or bad terrain, which has been a common feature in narrow-beam systems for land signaling, was not requested in any of the NDRC projects.

A comparison of the weights, angles, and ranges of the systems developed under NDRC auspices with those of earlier systems is given in Figure 1.

Ship Use. The type E system described in Section 4.4.2 was developed for secret night communication by voice within convoys at ACW distances up to 6.5 sea miles, code to 9 sea miles, with beam angles near 15 degrees, so that one ship could communicate with several others simultaneously. Its weight and power are compatible with ship operation. It can also be used for ship-to-shore harbor entrance communication.

The Touvet system described in Section 4.5.3 could be similarly used. It has similar voice range, with transmitter angle of 25 degrees and receiver angle of 2 degrees. It is an r-f system and offers a choice of six carrier-wave channels.

The type G system (not an NDRC development) described in Section 4.3.1 could be used for the same problem, but it has a narrow beam of 1 to 4 degrees and, consequently, more security against detection. It is to be mounted on a stabilized platform and guided by an auxiliary tracking system and is to have an ACW range of about 4 miles.

Aircraft Use. The *plane-to-plane* [P–P] system described in Section 4.4.4 was developed for secret communication between adjacent planes of B–29 bombing formations during the hours of approach to the target. The system was not completed because of the termination of the war, but it was designed to give angles of 120 degrees horizontally by 60 degrees vertically at the front and also at the rear of a bomber, with estimated ACW ranges of ½ mile in the daytime or 2 miles at night (with different circuits). Weight and power conform to Army Air Force requests.

The *plane-to-ground* [P–G] system described in Section 4.4.3 is for use in situations involving the maintenance of communications and transport of supplies by air at night to guerrillas, paratroops, or other isolated ground troops. The complete ground unit (type W, Section 4.3.2) weighs about 25 pounds and can be carried to earth on the person of a paratrooper. The complete plane installation of the P–G system would weigh 60 pounds and the transceiver

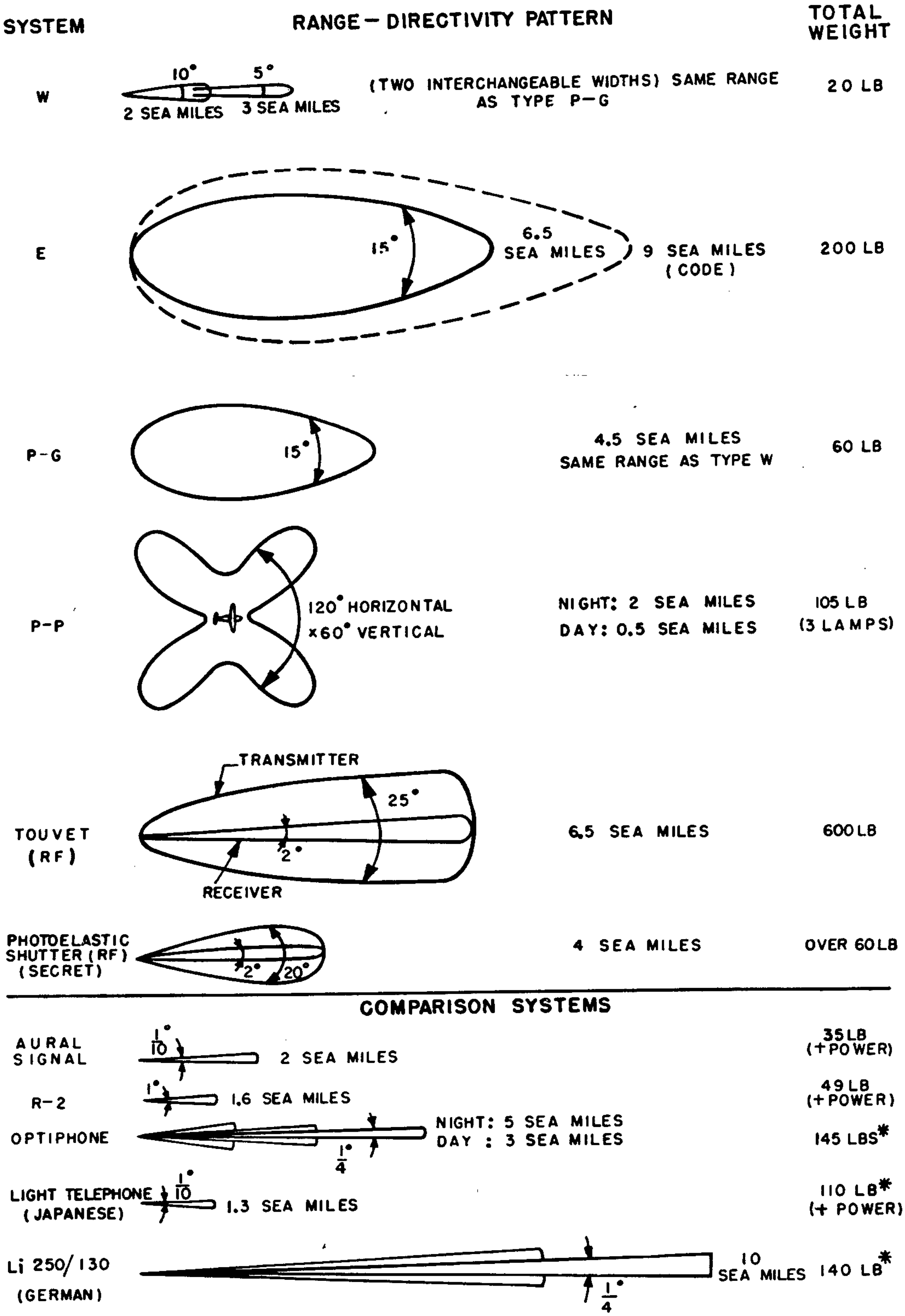


FIGURE 1. ACW ranges and angles of communication systems.

All patterns show ACW ranges between two similar systems, of which only one is shown. They are night-voice ranges except as indicated. Receiver and transmitter patterns are roughly identical except as noted. The P-P pattern is for planes flying parallel, but all other plots show the maximum range when the second system is pointing directly at the system shown. The starred weights refer to units produced to specifications for field use, which may be several times heavier than laboratory models of the same type.

would be hand-operated through a hatch door. The beam angles are about 15 degrees for the plane unit and 10 degrees for the ground unit. These are sufficient for making contact and maintaining communication between the hand-held units, which are guided with the help of auxiliary infrared electron telescopes. The ground-to-plane ACW range should be about 2 miles, plane-to-ground about 4 miles.

Ground Use. The ground unit of the plane-to-ground system just described was adapted from an ultraviolet hand-held unit developed for daylight communication between landing barges, with angles of 5 degrees and ranges up to 2 miles. The NIR adaptation (type W, Section 4.3.2) gives ACW ranges of 3 miles with the same beam angle and is most suitable for night communication. Apparently, NIR and UV sources and cells can be made interchangeable. Type W can be operated from the self-contained power supply for at least one hour. For longer operation, it may be connected to a 6-volt storage battery.

Mixed Use. If NIR systems become more common, communication between units of different types may become as usual as with radio. Most of the systems to be described will transmit to and receive from each other interchangeably.

In addition to the ship-to-shore and plane-to-ground arrangements described, there are other combinations. One might be ship to landing barge or beachhead, using type E, or preferably the stabilized narrow-beam type G on the ship and type W on the shore. Expected ACW ranges might be: type W (5 degrees) to type E, 3 sea miles; type E to type W, 4.5 sea miles.

Another combination would be ship to plane, from type E (which has high elevation angles) on the ship to the P–G system on the plane. The ACW ranges in either direction would be about 5 sea miles.

Since type W is portable and can be operated from a 6-volt battery, it is not restricted to ground use but may be carried on ships, planes, and tanks for short-range communication.

Various modifications of these systems have been proposed to give increased security in each of these applications, if and when enemy interception of messages should become a troublesome problem. It must be remembered that in most cases the added security is obtained at the expense of lowered efficiency and increased complexity.

Identification and Recognition. Another important military application of infrared radiation is the equipping of military units—ships, planes, tanks, infantry groups, trench positions—with secret, all-around view, continuously operated beacons broadcasting a unique signal, and with directed receivers so that the units are immediately identified as friendly by any other similarly equipped unit within range. Some systems designed exclusively for this purpose will be described in Chapter 5, but it should be pointed out here that the voice systems of the present chapter usually contain all the apparatus necessary for this purpose and can be adapted electrically with a minimum of revisions to do both jobs. Optically, the transmitters are not so well suited to do both jobs, as only the P–P system (Section 4.4.4) has the wide angle usually required for identification from all directions. However, the narrow-angle voice receivers could be used for search purposes, like the type D recognition system receivers described in Section 5.2, by sweeping them automatically and continuously around the horizon when they are not being used for communication. Further remarks on the duplication and overlapping of functions of the various systems will be found in Section 5.2.

The identification function was considered in the original request for development of the P–P system. The transmitters were to broadcast a code tone continuously when not communicating, and this tone was to be picked up on other planes by narrow-angle receivers bore-sighted with the guns so as to provide a warning signal when they were turned on a friendly plane. This function was later eliminated from the P–P system as the AAF decided to use another system for identification, but it could probably be performed by the P–P system with very little increase in weight or complexity.

Types of Systems

A beam of light or radiation has three properties: intensity, wavelength distribution, and polarization. The variation of any one of these by suitable modulation may be employed as the basis of a voice communication system. In a rough way, variation of intensity corresponds to *amplitude-modulation* [AM] in radio and variation of wavelength distribution to *frequency-modulation* [FM], although the analogies are not exact, since the receiver is not tuned to the "optical" frequency.

The desired property of the radiation is modu-

lated at lower *audio* or *radio frequencies* (a-f or r-f). Simple a-f modulation involves AM in the modulating and receiving circuits, and systems of this kind will be called *amplitude-modulation systems,* even though the property of the *radiation beam* which is modulated may not be the optical amplitude. If photodetectors with very short response times are used, another kind of modulation may be employed, consisting of an amplitude-modulated r-f carrier wave on which is superposed either an AM or an FM audio signal (see Table 1).

is now used, although some earlier studies involved sound pressure modulation of a manometric acetylene flame. For modulating the outgoing beam, electro-optical devices like the Kerr cell have been considered, but most military systems use mechanical modulation, with vibrating mirrors and beam-chopping devices in a-f systems or supersonic vibrations of some optical element in r-f systems.

Some NIR optical communication systems are arranged in Table 1 according to the optical property being modulated and the kind of modulation.

TABLE 1. Types of code and voice communication systems: (c) indicates code only; (v) voice only; [a] NCRC consultation; [s] NDRC study; systems in italics, NDRC developments.

1	2	3	4
	Optical property modulated		
Kind of modulation	Intensity*	Polarization	Wavelength
a-f (AM)	*Type D* (c) Type G[a] Type R-2		*Spectral modulation system* (proposed)
Mechanically modulated (tungsten)	Type W (v) Light-beam telephone (Japanese) Li 50, Li 80, Li 250–130[s] (German)		
Electrically modulated (tungsten)	*Type D-2* (c) ASE and others (British) F.F.115 and others (Italian)		
(gas)	*Type E* *Plane-plane* (v) *Plane-ground* (v) Aural signal unit (v)	Type L[a]	
r-f (AM) Mechanically modulated	Optiphone (a-f receiver only)	*Photoelastic shutter system*	
Electrically modulated	*V-M system* *Touvet system*		
r-f (FM)			

* There are two other intensity-modulated systems which do not fit easily into this table. One is an ordinary blinker code system which may be regarded as very low-frequency amplitude modulation. The other is a code or teletype Navy-developed system, type P, which makes use of very high-frequency spaced pulses of polarized light (see Section 5.1.2).

The modulation may be accomplished either by electrically modulating the radiation source or by using a constant-intensity source and modulating the outgoing beam. In the first case, electrical modulation of the current through a filament lamp (a-f) or through a gaseous discharge source (a-f or r-f)

The modulation technique may determine the size, power, efficiency, and security of the source and in some cases the design of the receiver.

The large number of voice systems shown in column 2 indicates that the intensity-modulated a-f type of system is the simplest in design and con-

struction. Most of the components of such systems are commercially available. The mechanically modulated systems are the lightest in weight; the electrically modulated ones can attain the highest efficiency of light utilization.

Security. Security against reception of intelligence by the enemy is called *message security*; security against detection by the enemy of the existence of a modulated infrared system is called *system security.* Since the systems of column 2 are numerous and simple, they have very little security of either kind when operated in close contact with the enemy. They have the NIR advantages of invisibility and limited range, and some also have the advantage of narrow-beam width, but they can all be received by any NIR a-f receiver. Speech-scrambling has not yet been used, but it could be incorporated in existing systems to improve message security. It would not affect system security.

American equipment for a-f detection of enemy NIR systems has been built (see Section 5.5). Presumably, foreign equipment for a similar purpose may shortly begin to limit the usefulness of the American systems shown in column 2. When that occurs, it may be possible to change some of the electrically modulated gas discharge sources to r-f FM, or to r-f AM with superimposed d-c, and thus make them secure against a-f receivers. Or it may be possible to go to systems like those in columns 3 and 4. Reception of intelligence from the transmitters of the systems in column 3 requires plane, or plane and quarter-wave, polarizing sheets over the receiver. Reception of intelligence from the transmitter of the recently proposed system listed in column 4 is more complicated, although the system promises to be simple to construct.

These added security devices all give message security. Greater system security may be obtained at present by using another wavelength region, the IIR. Work in the IIR requires a new type of detector cell, so far not extensively used, and it prevents reception of the message or detection of the source by the various and common NIR detectors.

The systems in columns 3 and 4 are necessarily less efficient than those in column 2 because of the additional complication of the equipment and the additional restrictions on the light beam introduced by the security devices. It is not yet certain whether the ranges of IIR systems will be as great as those of closely similar NIR systems.

4.1.3 Common Aspects of All Systems[b]

PRINCIPLES OF OPERATION

The operation of all these systems may be understood by referring to Figure 2, which is a schematic diagram of the type E system. Sound energy is converted to electrical energy by the microphone at the transmitter and is amplified by the audio-frequency amplifier to a level capable of modulating the transmitter current. This may be the current supplied to the source itself, if it is electrically modulated like the source in Figure 2, or it may be the current supplied to a mirror or other optical element located in the transmitter beam emanating from a

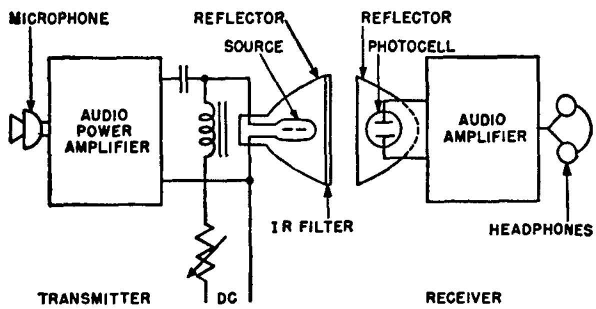


FIGURE 2. Block diagram of communication system.

steady source. The intensity, polarization, or wavelength of the radiation leaving the transmitter may thus, by one or the other of these methods, be made to vary in proportion to the modulating audio current and in accordance with the characteristics of the original sound. The reflector shown in Figure 2 may be replaced in other systems by a more complex transmitter optical arrangement. The radiation is directed toward the distant receiver through an infrared filter designed to eliminate the visible portion of the spectrum.

The small amount of infrared radiation reaching the receiver is concentrated by a mirror or lens upon the detector, which is generally a photoconductive or photoemissive cell. If the modulation is in the wavelength or polarization of the beam, it is converted to an intensity variation by a suitable device. The photocell current varies in magnitude with the intensity of radiation falling upon the cell, and the fluctuating current is a fairly accurate copy of the current modulated by the original sound at the transmitter. The fluctuating current is usually

[b] For list of symbols used in the equations of this section, see end of chapter.

changed by passage through a load resistor to a fluctuating potential which is applied to the input of the receiver audio amplifier. The electrical energy available at the output of the amplifier is converted again to sound by the headphones or loud-speaker. That these numerous conversions of energy can be accomplished without excessive distortion is indicated by the fact that conversation can be carried on over a distance of several miles with high intelligibility using systems based on such principles.

The Range Equation

The range of such a system depends on many factors such as the power and efficiency of the source, the responsivity of the detector, the beam angles, and the optical areas, but it depends most of all on the weather.[23,31] Knowledge of the relations between these variables is helpful in evaluating the components of a system or in predicting the overall performance of an untested system. The relations are formally independent of wavelength, and therefore the usual photometric (visible light) symbols may be used.

The fundamental range equation is

$$R_v^2 = I\frac{A}{F}, \tag{1}$$

where R_v is the vacuum range of a system, or the maximum distance that the receiver could be separated from the transmitter and still obtain intelligible communication if no atmospheric attenuation were present (at night, unless otherwise noted),

- I is the maximum effective beam intensity (candlepower),
- A is the gathering area, or entrance pupil, of the receiver optical system,
- F is the effective threshold flux falling on the receiver which is required for just-intelligible communication.

The equation can be derived from the primary definition of intensity I as the flux F per unit solid angle, since A/R^2 is the solid angle subtended at the transmitter by the receiver. This equation must be modified to take account of losses, and it can be rewritten to express I and F in terms of other variables.

Atmospheric Attenuation

Transmission. The most serious loss is the result of absorption and scattering by fog, smoke, and dust in the atmosphere. The absorption of two or three small bands of water vapor in the NIR may be neglected. In the NIR the transmission obeys Lambert's law to a good approximation, so that if T is the fraction of light transmitted through unit distance of atmosphere ($T < 1.0$) then the fraction transmitted through R units is T^R.

The values of T for the visible and the NIR may be taken to be almost the same at any given time.

Operational Range. The measured limiting operational range R_T of communication in weather with transmission T may be much less than the vacuum range R_v. The illumination E in an attenuated beam falls off as[31]

$$E = \frac{I}{R^2}T^R. \tag{2}$$

The threshold illumination on a receiver must be the same at R_T for transmission T as at R_v for transmission unity, or

$$\frac{I}{R_T^2}T^R = \frac{I}{R_v^2},$$

and

$$R_T^2T^{-R} = R_v^2. \tag{3}$$

The value of R_T as a function of R_v is plotted for several values of T in Figure 3. In practice, R_v must be computed from observed values of R_T and T, or it can be determined from measurements in the laboratory.

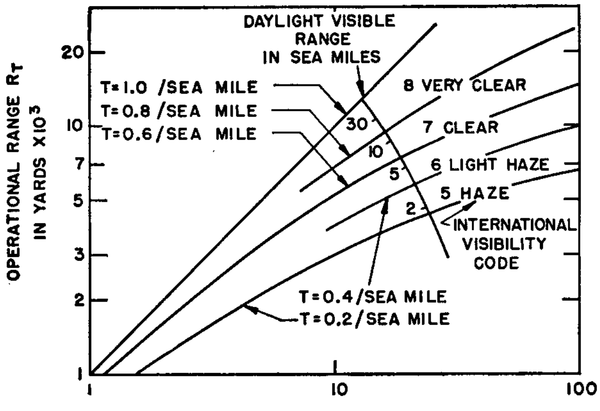


FIGURE 3. Atmospheric transmission and range.

Average Clear Weather. As R_v may be several times larger than actual ranges, it is convenient in comparing the performance of systems to specify another standard range, the range in average clear

weather [ACW]. Usually ACW is taken by the Navy to refer to a transmission of 0.6 per sea mile, and this range would then be denoted by $R_{0.6}$ in equations (2) and (3). (The phrase "0.6 per sea mile" is the accepted substitute for the awkward exact expression, "$0.6^{1/\text{mile}}$," which is necessary if T^R is to be dimensionless.)

This value of T corresponds to a loss in signal of 4.5 db per mile, in addition to the reduction by the inverse square law. A convenient rough rule is that the rate of loss in ACW, at distances over 5 miles, is about 6 db per mile. Thus a change by a factor of two in any of the variables determining range (beam intensity, detector responsivity, receiver area) changes the ACW range by about 1 mile.

In ACW the daylight visible range, as defined later, is about 7 sea miles, and the code number is 7 (clear) in the International Visibility Code.

While the ACW range is an easily interpreted index of the military performance of a system, it is not so satisfactory for laboratory or theoretical comparison of systems as the vacuum range. The ACW range involves arbitrary and not easily verified assumptions about attenuation at the wavelengths used, and computing it requires troublesome logarithmic conversions and reconversions.[31] The vacuum range should be more widely adopted as the measure of communication system performance. In this chapter, for systems for which the vacuum range has not been computed, an attempt will be made to estimate it so that the various systems may be more easily compared on an absolute basis.

In order to compute R_v or the ACW range from measured operational ranges, the value of T during the operation must be known. This may be found either from estimates of daylight visible range or from instrumental determinations.

Daylight Visible Range. The daylight visible range, or limiting range at which large black objects can just be seen against a white sky, is proportional to[37,38]

$$\frac{1}{\log(1/T)},$$

and varies more rapidly with T than does R_T. The visible range in good weather is greater than the range of a communication system, becoming infinite for transmission unity when the communication range only becomes R_v, but in murky weather it may be less than the communication range. The relation of T to the visible range and to the index numbers used in the International Visibility Code is shown in Figure 3.

From visibility estimates values of T may be determined to an accuracy of about 0.1 per mile. Obviously, the daylight visible range can be used to determine T for a night operation only if the weather appears to remain almost unchanged in the interim. The *visible range* must not be confused with the *night visual range* [NVR] or range at which a filtered NIR transmitter can be detected by the dark-adapted eye.

Instrumental Determination of T. Several different instrumental methods, none of them very satisfactory, have been used to determine T. The transmission may be found from absolute measurement of the flux received on a photocell from a fixed radiation source at a fixed distance of several miles. Or the signal level of communication between a shore station and a moving ship may be plotted against the distance, and the transmission determined from equation (2).[16,17] A variation of the latter method is to use not the signal level but the brightness of the distant source (compared to a known local source) as observed in an optical telescope or electron telescope. Besides the obvious experimental problems in such determinations, a fundamental difficulty is that the transmission over any path is continually changing and a consistent set of values is therefore rare; the spread of such determinations may be less than 0.1 per mile only if the transmission stays fairly constant.

Some very rapid "twinkle effects" which have been reported as interfering with voice and code communication (see "Operational Tests" in Sections 4.6.2 and 5.2) are probably of refractive origin rather than being due to true variations in T, but of course they further complicate the problem of measuring T.

Transmitter Factors

Steady sources and electrically modulated sources of radiation have already been described in Chapter 1. Methods of mechanical modulation will be described in the subsequent discussion of individual systems.

Modulation. The maximum effective beam candlepower I, in equation (1), from a transmitter is proportional to the fraction z of the steady radiation which can be modulated by the impressed communi-

cation signal. Attainable values of z differ considerably for various modulation methods and for various types of sources. This difference is seen in Table 2,

TABLE 2. Efficiencies of various modulation methods.

Source and method	Modulation efficiency
Cesium-vapor lamp; electrically modulated (up to 5,000 c)	2.00
Concentrated-arc lamp; electrically modulated (1,000 c)	0.30
Tungsten lamp; electrically modulated (1,000 c)	0.30
Vibrating mirror, opaque grid	0.50
Vibrating mirror, prism grid (Li 250)	1.00
Spectral modulation	0.50
Cesium lamp polarization system	0.50 (ideal; actual near 0.25)
Supersonic diffraction (optiphone)	
r-f crest to trough	1.00 (ideal; actual near 0.70)
a-f crest to trough	0.50 (ideal; actual near 0.35)
Rare gas carrier-wave lamps	
r-f crest to trough	2.00*
a-f crest to trough	1.00*
Photoelastic shutter	
r-f, averaged over shutter	0.35
a-f, averaged over shutter	0.25 (ideal; actual near 0.06)

* The intensity without the modulation device is taken to be the average intensity over an r-f cycle of maximum amplitude.

which gives the modulation efficiency for various methods. Electrical modulation of the cesium-vapor and rare gas sources is seen to be the most efficient method. The modulation efficiency is here defined as the maximum crest-to-trough change of radiant intensity producible by an audio signal, relative to the steady unmodulated radiant intensity of the same beam (with the modulating device omitted in cases where it is external to the source and obstructs part of the beam). So defined, the term is applicable to all modulation methods; for electrically modulated sources, it is twice the modulation ratio defined in Chapter 1.

The value of z mentioned above may be taken to be the relative rms variation of intensity with respect to the mean d-c intensity. For a maximum steady tone, z is $\frac{1}{2}\sqrt{2}$ times the modulation efficiency; for voice signal it is usually half or less of this value, depending on the transmitter circuits.

Pass Band. Maximum communication range demands not only maximum modulation of the source light but also a suitable choice of the modulation frequencies. If the strong low frequencies of the human voice are allowed to pass through the transmitter amplifier, they may reach amplitudes of overmodulation while the high frequencies important for intelligibility are still very weak. By cutting out the low frequencies in the amplifier, more energy may be put into the intelligibility frequencies without overmodulation. If the cutoff, for example, is at 1,000 cycles, 86 per cent of the energy is removed, permitting an increase of 17 db in the modulation of high frequencies with a loss of only 7 per cent in intelligibility.

This possible improvement has not been appreciated in many of the designs to be discussed, and some project control numbers have actually specified voice pass bands from 100 to 1,000 cycles, which would give very much smaller communication ranges. The optimum band-pass for optical transmitters needs careful study similar to that which has been given sound-powered phones.[41]

Removal of the low frequencies of speech causes much of the naturalness and identifying characteristics of the individual voice to be lost. For military applications this is of little consequence. Other ways to increase the intelligibility output are discussed under "Amplification" in Section 4.4.2.

Narrow-Beam Systems. The effective beam candlepower I depends also on the optical system. Consider first a collimating system with precision optical elements, that is, a system which focuses an image of the source at infinity. On looking back into such a system from the center of the beam at a great distance away, the exit pupil A_t is seen to be completely filled and of brightness about equal to the surface brightness B of the source. Then the effective intensity is

$$I = e_t' hzBA_t, \tag{4}$$

where e_t' takes account of the transmission and reflection losses in the optical elements and h is the *effective holotransmission* [ehT] of any NIR filter in the beam.[43] If the system consists of a simple lens, or reflector, of focal length f, the solid angle Ω_t into which the beam goes is determined by the effective *projected* area of the source, a_0'.

$$\Omega_t = \frac{a_0'}{f^2}. \tag{5}$$

High Efficiency. Such a system may be made more efficient by increasing I or A_t, with no change in

focal length or Ω_t. Or it may be made more efficient by increasing Ω_t through a decrease in f, with no change in A or I; in the latter case one way of utilizing the increased efficiency is by decreasing the source size and input power so as to restore the initial beam solid angle. Both these cases reach a limit when the largest practicable fraction e_t of the emergent flux φ from the source goes into the transmitter beam. The fraction e_t may be called the *transmitter efficiency*. Then

$$I = e_t hz \frac{\varphi}{\Omega_t}. \tag{6}$$

For large values of e_t (over about 0.25), reflectors must be used. The minimum area (exit pupil) A_t required for them is given approximately by

$$A_t = e_t a_0 \frac{\pi}{\Omega_t}, \tag{7}$$

where a_0 is the total luminous surface area of the source.

Since in most communication systems the highest efficiency is desired, equation (6) is fundamental. It is applicable also to noncollimating systems and wide-angle systems generally, with or without beam-spreading devices.

Usually, in the systems to be considered, the values of Ω_t were not so small nor the source areas a_0 so large as to make the efficient reflector size A_t prohibitive.

From the proportionality between a_0 and Ω_t in equation (7) we see the general rule for choosing the source for a given communication problem: wide angle, large source; narrow angle, small source.

The total emergent flux φ from a source may be thought of as proportional to the product of the input power and the *hololuminous efficiency* in hololumens per watt. This efficiency is of the order of 15 hlm per watt for all the sources considered here except the Western Union concentrated arc (Section 4.4.2); for the latter, it is only 3 to 5 hlm per watt for arc sizes near 100 watts.

Beam Solid Angle. Equation (6) implies that the beam has uniform intensity within angle Ω_t and zero outside. In practice, with most beam distributions considered here, equation (6) holds approximately if Ω_t is taken to be bounded by the directions in which the beam intensity falls to *half the peak intensity* [hpi]. Only hpi solid angles and beam widths will be used hereafter.

The relation between I and Ω_t is of the greatest importance in the design of optical communication systems. To obtain maximum intensity and communication range with minimum source power, the beam must be as narrow as possible for the desired purpose. For a given source, power, and optical efficiency, wide-angle systems are short-range systems.

Laboratory Methods. Candlepower distributions may be measured by placing a source or a transmitter optical system, as the case may be, on a rotating table and determining the response of a fixed detector at some distance away as a function of angle. The distance away must be great enough that the angle subtended by the source at the detector is small compared to the hpi width.

The ratio between the maximum candlepowers, I from a transmitter system and I_0 from its bare source alone (both a-c or both d-c measurements), is the *transmitter optics factor, O_t*

$$I = I_0 O_t. \tag{6a}$$

The vacuum range R_v from a given transmitter to a given receiver may be determined in the laboratory by finding the maximum communication range from the bare source to this receiver and multiplying this value by $\sqrt{O_t}$.

If the source is too intense to measure the latter range directly in the laboratory space, it may be measured indirectly by reducing the source intensity by a known amount as follows.[9] A lens or mirror is set up so as to form a reduced image of the source, and so that the receiver can "see" only this image. The intensity from this image is less than the intensity of the source by a factor p^2/q^2, where p and q are the object and image distances from the lens or mirror. The communication range from the image to the receiver is thus less by a factor p/q than the range from the bare source itself.

Choice of Filter. Commonly, a maximum permissible NVR is specified in the requirements for an NIR system. The NVR is defined as the visual range limit of a transmitter to the dark-adapted standard eye in total darkness. It is determined by the kind of source, its holocandlepower, and the kind of filter, as discussed in Chapter 2.

The specified NVR should be made as great as is militarily feasible because the larger the NVR is, the greater the operational range can be for a given transmitter system. This results from the fact that the ehT and the *effective visual transmission* [evT]

of a filter type vary together with changing optical density. Of course the filter type must be chosen from among those with satisfactory weathering properties and thermal and mechanical stability for military use. It should be a type which will make as great a differential as practicable between the ACW range and the NVR. This means it must have a high index of merit (see Chapter 2) if this can be obtained in conjunction with a reasonable ehT so that the input power needed to obtain the desired ACW range will not be excessive.

With a specified NVR and a chosen filter type, the thickness or density must then be chosen to bring the NVR right up to the specified limit so as to make the communication range as great as possible.

The NVR for a given transmitter may be determined by computations for the standard eye according to the methods outlined in Chapter 2, or it may be determined for actual observers in the laboratory, reducing the range by a known amount as described above under "Laboratory Methods," so that the test may be accommodated in a limited laboratory space.

RECEIVER FACTORS

The contribution of the receiver to the range is represented by the term A/F in equation (1).

Effective Threshold Flux (*Signal Equivalent of Noise*). The value of F depends on the spectral distribution of the radiation and on the spectral response of the detector cell. All other factors being equal, the type of cell chosen must naturally be that giving a maximum *signal-to-noise* [S/N] ratio for the given spectral distribution and audio- or radio-frequency distribution of the modulated radiation from the filtered NIR source. What the best source or filter is also depends on the cell; actually no one of them should be chosen independently, but all combinations should be studied to find the best for a particular problem. In addition, the value of F depends upon what fraction e_r of the flux falling on the receiver entrance pupil actually reaches the photodetector cell.

The threshold flux is determined by the limitation of intelligibility because of the noise in the cell and circuit. In circuits with low noise, the noise is generally a function of the effective cell area a and receiver band width Δf, as explained in Chapter 3. The ratio of the rms threshold signal to the rms noise, *threshold S/N*, depends on whether the communication is code or voice, on the kind of source and cell, and the circuits.[18a] This ratio may be lumped with other constants into a constant k.

Finally, then

$$F = \frac{k}{e_r}\sqrt{a\Delta f}. \qquad (8)$$

This flux must be made as small as possible in order to obtain maximum range.

Bandwidth. One way to make F small is to decrease Δf. For carrier-wave [c-w] code reception it may be decreased until the tuned receiver circuit is set into self-oscillation.

For voice reception, when Δf decreases, the S/N ratio required for intelligibility increases, causing an increase in the constant k. The rate of increase of k depends on the shape of the frequency-response curve and the frequency of peak response. The experimental work on the type E system (see "Preamplifier" in Section 4.4.2) indicates that the values of $k\sqrt{\Delta f}$ and of the flux F required for speech intelligibility are a minimum for a peak response near 1,500 cycles per second with a bandwidth (6 db down) of about 700 cycles per second. In later work on the aircraft systems (see "Amplifier" in Section 4.4.3), it seems that better intelligibility may be obtained if this pass band is *not* sharply limited on the high-frequency side. The results of studies on pass bands and noise in sound-powered phones[41] and similar devices should be applied to this problem.

Cell Area and Solid Angle of View. Another way to make F small is to decrease the effective cell area a. With a given optical system this involves a proportional decrease in the solid angle of view Ω_v. The angle Ω_v will be taken as bounded by the directions in which the receiver response falls to *half the peak response* [hpr].

If a given hpr receiver solid angle is specified, it may be obtained with a smaller and smaller cell area (and higher and higher sensitivity) by decreasing the focal length of the receiver lens or reflector up to a certain point. The limiting cell area is given by the relation[18,23]

$$a = \frac{\Omega_v}{\pi}A. \qquad (9)$$

In practice, as a result of optical aberrations, the minimum value of a is some 50 per cent greater than this value.

This limit is reached with an f/number of the optical system of about $f/0.5$ for a one-surface detector like a phototube; f/numbers down to about $f/0.1$ may be used with two-surface detectors like *thallous sulfide* [TF] photoconductive cells (see Chapter 3), if they are mounted with their sensitive surfaces parallel to the axis of a reflector. The effective cell area a of a two-surface detector mounted thus is approximately the area of the double surface. Such a detector thus can have twice the solid angle of view of the same size one-surface cell for the same effective mirror area.

Mirrors are required in order to attain either of these f/numbers. With further decrease of the focal length below the values implied by these f/numbers, the mirrors get deeper and deeper, and the average distance of the cell from the mirror surface increases. Then a must *increase* in order to keep Ω_v constant, which causes the attainable receiver sensitivity to decrease again.

For a maximum sensitivity, then, with a given A, the value of a required is given approximately by equation (9).

The smaller the angle of view required, the higher the sensitivity of the detector cell which may be used. This parallels the relation for transmitters between beam angle and intensity and leads again to the conclusion that a wide-angle system is a short-range system.

However, it is less important to have a small solid angle at the receiver than at the transmitter, since the best receiver sensitivity is inversely proportional only to the square root of the solid angle of view, while the transmitter intensity is inversely proportional to the beam solid angle itself.

Laboratory Methods. The directivity pattern of receiver response as a function of direction may be determined in the laboratory by placing the receiver on a rotating table to detect a weak source some distance away. The hpr angle of view may be found from this pattern.

If the photodetector and associated circuits are linear, the ratio of the maximum response of the cell in the optical system in a uniformly illuminated field to the maximum response of the cell alone is called the *receiver optics factor* O_r. In cells uniformly sensitive over their surface, O_r is equal to $e_r A/a'$, where a' is the projected area of the cell. A bare cell may be used for laboratory range measurements, and the range so obtained multiplied by $\sqrt{O_r}$ gives the range for the assembled receiver optical system.

Backscatter. One practical limitation on receiver sensitivity in a two-way communication system is commonly the noise produced by radiation from the adjacent transmitter beam scattered back into the receiver by nearby objects or just by atmospheric haze. The backscatter from nearby objects may be avoided by proper location of the system.

The backscatter from haze has been shown theoretically [39] to be proportional to $\alpha^2\beta/d$, where α is the hpi beam width, β ($\geq \alpha$) is the hpr receiver width, and d is the distance between centers of transmitter and receiver. It is not certain whether this analysis takes into account current ideas outlined above concerning the relation of receiver sensitivity to angle of view. But the general conclusion is certainly correct: the noise is large when the hpi and hpr angles are large, and also when transmitter and receiver are close together. The latter is commonly the case, the two units being placed together in a single transceiver head for convenience.

Backscatter in wide-angle systems having a transceiver head may make duplex operation impossible. In duplex, transmitter and receiver are continuously ready to operate, permitting great naturalness of conversation. But if the transmitter feeds back optically into the receiver, it may drown out the distant station, and send-receive operation must then be used, with the transmitter and receiver energized alternately, as with a press-to-talk button. In this case, the transmitter line must be filtered from any modulation or ripple when the system is in the receive condition. Even so, photocurrent noise from the remaining steady backscattered radiation may still be serious. If so, the transmitter intensity must be reduced or turned off altogether, either electrically or by a mechanical shutter, during reception, in order to achieve threshold sensitivity.

Daylight Operation. The noise produced by steady backscatter is trivial compared with that produced in phototube and TF cell receivers by daylight. The operational ranges of NIR systems in daylight may consequently be much decreased from night ranges. (Ultraviolet systems are not so much affected, as they can be filtered to receive only waves shorter than 2,900 μ where almost no sunlight comes through the ozone layer in the atmosphere.)

In vacuum phototubes, the noise increases as the square root of the d-c current, which is proportional

to the total steady flux received. For a uniformly bright field of view, the flux is proportional to the product of Ω_v and A. With gas-filled phototubes and TF cells, the expression for the change produced by background light is less simple. The TF cells are less affected than either kind of phototube, but with these cells there is the additional complication that the cell resistance is decreased by the illumination, necessitating a change in the load resistor if optimum performance is to be maintained (see "Preamplifier," Section 4.4.4, for a circuit which may eliminate this complication). It seems that lead sulfide (PbS) photoconductive cells are very little affected by steady background light (Chapter 3).

With detectors which are affected markedly by background radiation, very narrow-angle systems are much less affected by daylight than are wide-angle systems both because the solid angle of view is smaller and because, with Army (land) systems at any rate, a smaller fraction of sky is included in this solid angle. The Lichtsprechers (Section 4.3.1), which have hpr angles of 1/4 degree and PbS cells, seem to have no loss of range in daylight. The Japanese light-beam telephone mentioned in Section 4.3.1 has an iris diaphragm over the receiver cell to give a large angle at night and a small angle in the daytime.

This Japanese system and some other phototube systems with hpr widths less than 1 degree showed changes of about 20 per cent between the night and day vacuum ranges,[9] but the cells used had very high noise which would reduce the apparent size of the effect. The daylight vacuum range of the Signal Corps optiphone (Section 4.5.1), which has a similar receiver, seems to be less than the night range by a factor of about 3. In one test on TF-cell receivers with all-around view, background illumination equivalent to an overcast north sky caused a loss equivalent to a factor of 3 in vacuum range, even with proper load resistor adjustment (see "Preamplifier," Section 4.4.4).

Probably none of the systems to be described (except perhaps those using PbS cells) will work if sunlight falls on the receiver. An NIR filter and a sunshade over the receiver may materially improve daylight communication with the wide-angle systems and use of a PbS cell may bring still greater improvement. More experimental work on these points is needed.

Experiments with operation of a wide-angle TF-cell receiver in the presence of searchlights, star shells, and gun and shell flashes are reported under "Operational Tests" in Section 4.4.2.

Revised Range Equation

Combining equations (1), (6), (8), and (9), we have for the limiting vacuum range

$$R_v^2 = \left(\frac{e_t e_r}{k\Delta f}\right) hz \frac{\varphi A}{\Omega_r \sqrt{a}}, \tag{10a}$$

or

$$R_v^2 = \left(\frac{e_t e_r \sqrt{\pi}}{k'\Delta f}\right) hz \frac{\varphi \sqrt{A}}{\Omega_t \sqrt{\Omega_r}}, \tag{10b}$$

or

$$R_v^2 = \left(\frac{e_t e_r \pi}{k''\Delta f}\right) hz \frac{\varphi \sqrt{a}}{\Omega_t \Omega_r}. \tag{10c}$$

The change from k to k' and k'', in equations (10b) and (10c) respectively, is introduced to take account both of the deviation of actual systems from the ideal limit case given by equation (9) and also of certain geometrical factors which depend on the shape of the detector cell.

Equations (10b) and (10c) are generally the most useful in designing a communication system since they involve the solid angles explicitly, and these are usually among the first military characteristics specified. The last equation has the further advantage that it involves the detector cell area explicitly, and this quantity may be fixed by commercial availability for cells of a given type.

The ranges R_v are of a different order of magnitude from the limiting ranges encountered, for example, in radio communication. Thus the maximum value of R_v theoretically obtainable from a 100-watt source with beam widths of about 15 degrees, 18-inch mirrors, and present detector cells is of the order of 50 miles. This corresponds to an ACW communication range of about 8 miles. While this short range is unsatisfactory for many military purposes, it does offer the advantage that the range of enemy detection, even with specially designed search receivers, is also limited to distances of the same order of magnitude.

Auxiliary Equipment

A number of auxiliary devices are commonly used with NIR communication systems, such as NIR

image-forming devices (image tubes) for visual sighting on a distant source; stabilized platforms (stable tables) with NIR, IIR, or *far infrared* [FIR], 8 to 13 μ, training devices to maintain alignment automatically especially with narrow-beam systems; and test or monitoring devices to check transmitter and receiver operation.

Image Tubes. The types now used on equipment to be described include the charged-phosphor type AM metascopes and types C_3 and C_4 electron telescopes. These are described in the Summary Technical Report of Division 16, Volume 4.

Stabilized Platforms. Wide-angle systems, with beam angles over about 5 degrees, depending on the military use intended, may be mounted on gimbals and manually trained on the distant source with the help of an image tube. All-around systems, with beam angles over some 100 degrees and the resulting great reduction in range and security, are used only where manual guiding is very undesirable and where a transceiver is to be fixed in position on a moving craft or vehicle.

Narrow-angle systems, with beams less than 5 degrees, may be used from moving stations only if the systems are automatically guided. They may be guided by focusing radiation from the distant station on a split detector cell and applying the amplified differential signal from opposite halves or quadrants of the cell to a driving motor. This motor then rotates the apparatus so as to keep the distant station centered in the field of view. The cell may respond to an NIR source or beacon or it may respond in the IIR or FIR to the naturally emitted heat radiation from the other station (provided it is a ship or a heated vehicle).

If the NIR is used the cell might be the detector cell of the communication system, though cells and circuits for such an arrangement have not been worked out; the distant source might be the communication source, although an all-around beacon is better as the systems are then not so troublesome to line up initially.

For Navy use, where the only variable coordinate of the distant ship station is its azimuth, tracking is simplified by mounting the system on a gyroscopically stabilized horizontal platform; then only a two-element tracking cell is needed. The transceiver units must be very light in weight to be used with present platforms. In experimental BuShips tests successful tracking from such platforms to ±½ degree of arc[c] has been obtained with FIR systems trained on small ships at distances up to 4 miles in average weather.

Test Devices: Microbeacon. Source monitoring devices are necessary for checking proper transmitter operation in some of the polarization systems, but for most voice systems to be described the operation is adequately monitored by simple visual or image-tube observations without any additional apparatus.

Similarly, detector cell and receiver operation is usually checked simply by listening for the characteristic hiss of cell noise in earphones or loudspeaker and noting the increase in noise produced by placing a light, a match, or a cigarette in the field of view. For more guarded and accurate field testing, two portable *microbeacon* test sources have been constructed by University of Michigan Contract NDCrc-185.[40]

The first microbeacon, shown in Figure 4, is operated from a 110-volt 60-cycle per second a-c ship supply. It consists of a small tungsten lamp whose light is modulated by a sector disk used as a mechanical chopper at 90 or 1,500 cycles per second as desired. A virtual image of the source is formed by the polished surface of a steel ball, the intensity being thus diminished as discussed in "Laboratory Methods," in Section 4.1.3. The light from the image passes out of the box through an aperture covered by a suitable NIR filter. A variable resistor in series with the tungsten lamp has a dial calibrated to read the emergent NIR flux in mile-holocandles (see Appendix).

In operation the beacon is held at some standard distance, such as 10 feet, from the receiver to be tested. It is pointed at the receiver and the lamp resistor is adjusted until the code tone can barely be detected above the noise. The receiver is pronounced satisfactory or unsatisfactory according as the emergent flux from the beacon is then below or above some specified maximum allowable value.

The second microbeacon [40] is an ingenious, constant, and simple device, which was constructed for checking the operation of the plane-to-plane recognition system (Section 5.3), but which would be equally applicable, with appropriate frequency changes, to any other NIR receiver. A ¼-watt neon

[c] Information supplied by courtesy of Section 660E, Bureau of Ships.

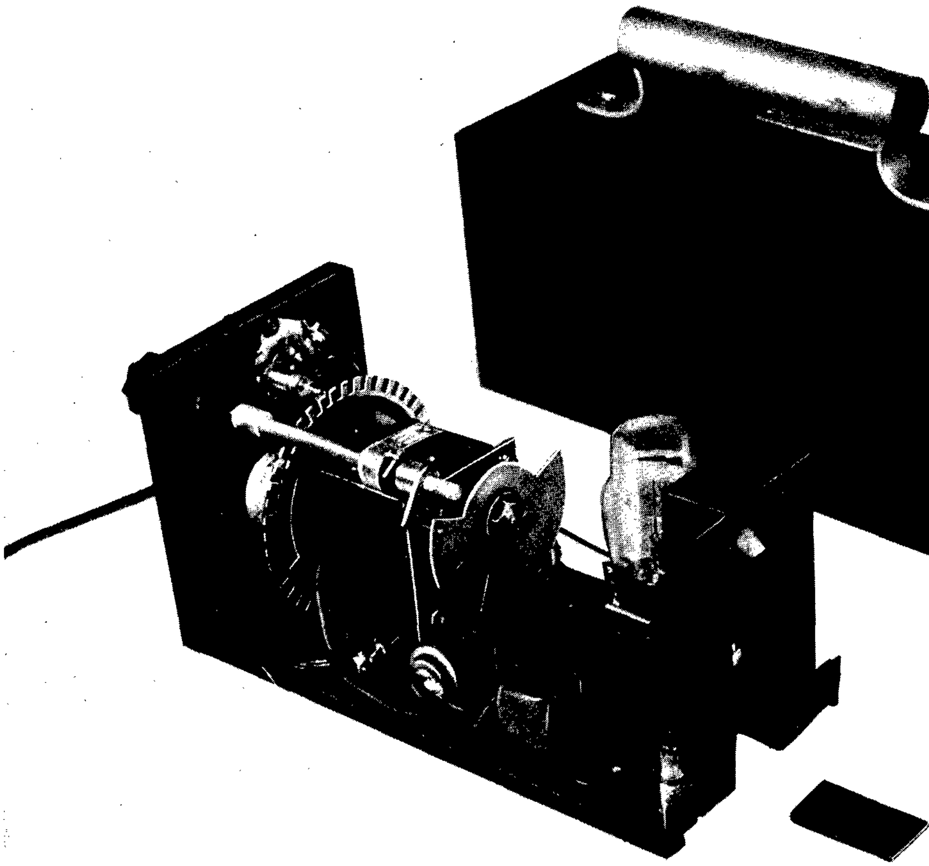


FIGURE 4. Microbeacon test source, with cover removed.

lamp acts both as a 90-cycle per second relaxation oscillator and as a source of light. Two other neon lamps serve as voltage regulators to compensate for the aging of the 200-volt batteries, and one of these lamps serves as an indicator of battery deterioration. The unit, including batteries, is in a box 3x4½x10½ inches in size, and may be held in one hand in front of the receiver to be tested. The intensity and frequency of the lamp are almost independent of temperature or of the age of the battery.

One of the code systems to be described in Chapter 5 also has a build-in microflux lamp for testing receiver operation. Such a method could be easily adapted for use in the voice systems discussed in this chapter, if desired.

4.2 PRE-NDRC SYSTEMS; GENERAL DISCUSSION

The success of optical voice communication systems has been dependent on the sources and sensitive detector cells available (that is, past the laboratory experimental stage) at any given time. As for sources, voice modulation of carbon arcs, manometric flames, and probably filament lamps was used before the turn of the century. Successful vibrating-mirror and vibrating ribbon-shutter systems for speech frequencies were produced in the sound motion-picture research during the 1920's. Efficient modulable gaseous discharge sources of infrared radiation became available only in the last decade.

Selenium photoconductive cells were the only in-

frared audio receivers in the early years of the century. The Case Thalofide cell (Section 3.3.1) appeared during World War I. Cesium-surface phototubes were first produced commercially in the early 1920's. Lead sulfide cells and other IIR detectors are the products of the last ten years.

4.2.1 Early German Work

A bibliography and discussion of some early optical voice communication systems have been given by Thirring.[1] As early as 1901, Simon in Göttingen obtained ranges up to 1 km with a 3-foot searchlight having a voice-modulated arc, and much greater ranges were claimed by Rühmer in 1904. The first successful systems from a military point of view were developed by Simon (Germany) and Thirring (Austria) working in cooperation with the Siemans-Halske Company in 1917.

The Thirring system was put into production but did not reach the front before World War I was over. The usual source was a 14-inch searchlight, with the arc modulated by inductive coupling between its circuit and the circuit of a carbon microphone. Glow discharge lamps, 5-watt *Nachtlampen*, and others were also used successfully in such a reflector but gave shorter ranges. The receiver employed a 1-millimeter selenium photoconductive cell on which the electrodes were placed in a grid arrangement. This was set at the focus of a 22-centimeter diameter, 30-centimeter focal length lens. It was connected to headphones through a four-stage triode amplifier. The receiver sensitivity was limited only by cell noise, which was high; the variation of cell noise with cell area is discussed in Thirring's paper.

The system is reported to have had an ACW voice range of nearly 8 kilometers (5 miles) and a much longer range with a buzzer code tone which was used for a call signal. The angles were probably about 1 degree for the transmitter and $\frac{1}{4}$ degree for the receiver. The system apparently was designed to be portable by two men and to operate from a gasoline generator.

No filter is mentioned in the account. Perhaps the beam was narrow enough for security without it. A weak infrared filter could have been used as selenium cells can be constructed to respond near to 1 μ.

It is likely that this system was the predecessor of the Lichtsprecher systems to be described later which were produced for the German Army sometime before 1934 and which figured in World War II. The Zeiss Works were associated with both systems and there are a number of common features, for example, in the receiver design.

An interest in very narrow beams (under 1 degree) characterized the early German studies. This, together with the static character of the last war which made possible prepared and stationary positions for transceivers, guided subsequent work there and elsewhere almost exclusively into narrow-beam systems up until the studies reported here. A narrow beam makes for great security, but such systems easily get out of alignment and are hard to line up again in field use, hence they are quite unsuited to mobile warfare. This may be one of the reasons why the Lichtsprechers and the Japanese narrow-beam systems were of so little military importance in World War II even though they were commercially produced for many years and although such secret, wireless, voice communication devices were greatly desired for military purposes even in World War I.

Several ingenious German visual blinker code devices of higher security were evolved during World War I which were based on polarization-modulation and spectral-modulation of the light beam.[2] One of these may have reached the production stage.

4.2.2 American Systems in World War I

Invisible ultraviolet and infrared blinker systems saw field use in World War I in guiding airplanes to landing fields and in keeping convoys together.[4] The ultraviolet sources were observed with telescopes having a fluorescent screen in the focal plane. The infrared sources in the convoy system were detected by a receiver using the Case Thalofide cell (Chapter 3). Receivers converting the infrared for visual blinker observations were, of course, not possible then nor for another 20 years until after the development of phosphors and infrared photoemissive cells and great advances in electron optics.

Case Code System

An infrared system apparently similar to this convoy system was demonstrated by the Case Research Laboratory in October 1917 to representatives of

the Army and Navy.[3] In this demonstration the Thalofide cell was mounted in a 24-inch reflector and was part of a triode oscillator circuit connected to earphones. Reception of a signal by the cell caused a change in its resistance and a change in the pitch of the audio note in the phones. The source was a 60-inch Sperry searchlight covered by a shutter and filter. The filter was made by combining Wratten filters 91, 45, and 53 into a single unit called Wratten 740, which was sealed at the edges against moisture. This filter has a cutoff near 0.8 μ, and transmits 50 per cent at 1 μ.

With this system, infrared blinker signals over a range of 18 miles from Fort Hancock to the Woolworth Building caused very distinct changes of pitch in average weather. Further tests were carried out in February 1918 with the Coast Artillery at Fort Monroe, Virginia.

At the end of World War I smaller versions of this system had been built for two-way communication. In these, the receiver and transmitter both had 8-inch mirrors and were incorporated in a single transceiver head. The source was an 8-volt signal lamp and the beam was modulated by a butterfly shutter. The system operated from a storage battery, had a range of 4 miles, and could be carried by two men.

Case Voice System

Two voice systems were also constructed. In these the source was an acetylene flame, modulated by speaking into a horn connected to the base of the burner. This source was about ¼ square inch in area and had an intensity of about 150 candlepower. The receiver was the Thalofide cell feeding into a three-stage amplifier.

When the source and cell were each used in 24-inch mirrors, the range was 5 miles on a clear night. Beam angles were probably of the order of 4 degrees.

With 12-inch mirrors, a 2-mile range was obtained, probably with beam angles of about 8 degrees.

This work was not carried further after the conclusion of World War I.

Later Work

American laboratories also studied voice-modulated carbon-arc systems, but apparently without any results of military value.

Later work was carried out principally in the development of sound motion pictures. These have all the elements of optical communication, plus a troublesome intermediate stage of recording on film. Much study was devoted to sources, methods of modulation, and detectors, though with emphasis on ultraviolet rather than infrared radiation. Descriptions of this work may be found in the technical journals of the period, such as the publications of The Society of Motion Picture Engineers.

The elements produced by this research were used from time to time in short-range demonstration exhibits to amaze the curious by "talking on a beam of light." Similar short-range systems, such as QST, have been presented as playthings in radio amateur magazines, but appear not to have been intensively developed further in this country for military purposes until the start of World War II.

4.2.3 Existing Systems at Beginning of NDRC Studies

At the time NDRC began work on optical communication systems, the systems now known to have been in operation were the German and Japanese vibrating-mirror systems and an Italian system with a modulated tungsten lamp (see Sections 4.2.4 and 4.3.1). The German units used TF-cell and PbS-cell receivers, having changed from the selenium receivers of the Thirring system after Case's discovery of the thallous sulfide cell. The other systems employed phototubes.

Another German system which reached the stage of an experimental field unit during World War II was apparently an r-f FM system using a cadmium compound for a detector cell and perhaps an infrared mercury lamp source (Section 4.5.1).

The British at that time were working on several tungsten lamp systems, all with phototube receivers (Section 4.2.4).

In this country, experimental models of the following systems were being developed: the Signal Corps optiphone (Section 4.5.1), using supersonic diffraction; the Western Union aural signal unit (Section 4.4.1) using a modulated arc; and the RCA type R-2 (Section 4.3.1) with a vibrating mirror. Studies were also being carried out with a Kerr cell polarization system (Section 4.6.2). All these systems had phototube receivers. Both the foreign and American systems had narrow-angle transmitters with beams 1 degree wide or less; most of them had

narrow-angle receivers suitable for daylight operation.

This information is based only on accessible reports and is necessarily incomplete.

4.2.4 Modulated Filament Lamp Systems

Systems using a modulated tungsten filament will be mentioned here briefly for reference, since this is an important type of modulation device even though it was not used in any of the voice systems developed by NDRC. Two code systems of this type, the type D–2 recognition system and the plane-to-plane recognition system will be described in Sections 5.2 and 5.3, respectively.

The advantage of such systems is that the source arrangements are small and uncomplicated. Like the modulated arc lamps they have no moving parts, and the lamps are commercially available. The disadvantage is that the modulation ratio depends on the heating and cooling time of the filaments. For voice modulation they must, therefore, be made of very fine wire; but even when they are so fine as to be fragile, the ratio of modulated to total light is not very large at the speech frequencies over 1,000 cycles per second which are important for intelligibility. Obtainable ranges with such voice systems are therefore small. Another disadvantage for voice use is that the light output is a very nonlinear function of either current or voltage. These features are drawbacks only with voice modulation; for code operation, at low frequencies, modulated tungsten lamps are very good sources and give good communication ranges.

ITALIAN PHOTOPHONES

Two Italian voice systems, the type F.F.115 photophone and another similar system using concave mirrors instead of lenses in the optical system, make use of modulated tungsten filaments of about 2-watt rating. The beam angles are about 0.5 degree.

BRITISH SYSTEMS

Several British narrow-angle systems are similar to the Italian ones. All have cesium phototube receivers. None has over about 1-mile range in daylight; perhaps the night ranges are two or three times as great.

A British wide-angle system, the ASE photophone, using a modulated 2-volt 1-watt tungsten source with a 10-degree transmitter beam, was designed for communication at night between moving infantry groups at distances up to 200 yards. A 360-degree all-around response was obtained by using a semicylindrical S/T thallous sulfide cell. The transceiver unit weighed about 25 pounds. This system may be compared with type W (Section 4.3.2) which might be used for the same purpose. The latter has about the same weight and size but much greater range because of its higher transmitter power and smaller receiving angle. The advantage of the larger receiver angle in the ASE system is that the unit is continuously ready to receive from any direction without a prearranged schedule. Whether this advantage is worth the sacrifice in range is for the Armed Services to decide, but it would seem that modification of the ASE system in the direction of type W would make it much more useful.

4.3 VIBRATING-MIRROR SYSTEMS

Audio-frequency mechanical modulation is now the most common method used in near infrared military communication devices. The simplest mechanical method is the use of a rotating "chopping disk" (type D system), but this is capable of only a limited kind of code communication and will be described in Section 5.2.

The other mechanical voice-modulation devices are the vibrating ribbon-shutter, used extensively in sound motion pictures, and the vibrating mirror. Only the latter has been used in NIR military communication systems.

In the basic vibrating-mirror arrangement, the light is split by a grid into bands which are reflected from an oscillating mirror onto another (identical) grid. The bands move back and forth across this second grid with the motion of the mirror and are thus transmitted by the second grid with variable intensity corresponding to the voice modulation.

4.3.1 Other Foreign and American Systems

TYPE R–2

In the simplest arrangement, used in the RCA type R–2 unit,[10] the grids are opaque, and are used with a lens system. This system has a 1-degree hpi width and a 3-degree hpr width. The detecting cell is an RCA 921 phototube. The equipment is portable

and weighs about 49 pounds. It has a night infrared ACW voice range of about 1.6 miles. The excellent mirror galvanometer is based on the one used in RCA sound-recording systems and has a flat response from 200 to 3,000 cycles per second.

Type G

The R–2 system was used as the basis for the design of the Navy type G system by the same company. The latter is a narrow-beam system of higher power to be mounted on a stabilized platform with FIR training system for ship-to-ship communication at distances up to about 4 miles. It was thought that this might replace the type E ship system (Section 4.4.2), giving greater security than type E because of the narrow beam. The engineers working under Contract OEMsr–990 to develop the latter system were consulted in the development of type G, and recommended the replacement of the receiver phototube by a TF cell (for reasons listed in discussing "Photodetector Cells" in Section 4.4.2) and supplied information on receiver circuits and on conditions for the use of such cells.[d]

Japanese Light-Beam Telephone

Other vibrating-mirror systems involve more sophisticated variants of this grid design. In the Japanese light-beam telephone,[9] the opaque strips of the second grid are aluminized on one side so that they reflect the incoming light to the receiver. (Type W, to be described in Section 4.3.2, employs a much more ingenious reflecting grid.) Transmitter and receiver thus use the same optical aperture, and the design is made very compact. The receiver employs a phototube. The hpi and hpr angles are 0.1 degree and about 1 degree, respectively, and the night infrared ACW voice range is about 1.3 miles. The weight of the field equipment is 110 pounds exclusive of power supply.

German Lichtsprechers

Three German vibrating-mirror systems were in field use in World War II. They are the Lichtsprecher (abbreviated "Li") 60/50, the Li 80, and the Li 250/130, all made by Zeiss.[5,6,7] The numbers refer to the transmitter-receiver apertures in millimeters. The field equipments weigh 30, 54, and 140 pounds, respectively. All have narrow beams, down to $\frac{1}{4}$ degree; the ACW day or night voice range of the largest is probably over 10 miles. The small effect of daylight and the very great ranges probably result from the insensitivity to background light of the PbS receiver cells used in these systems for the last five years, and from the extension of the spectral response of these cells into the IIR where atmospheric attenuation is less serious (see Section 4.8).

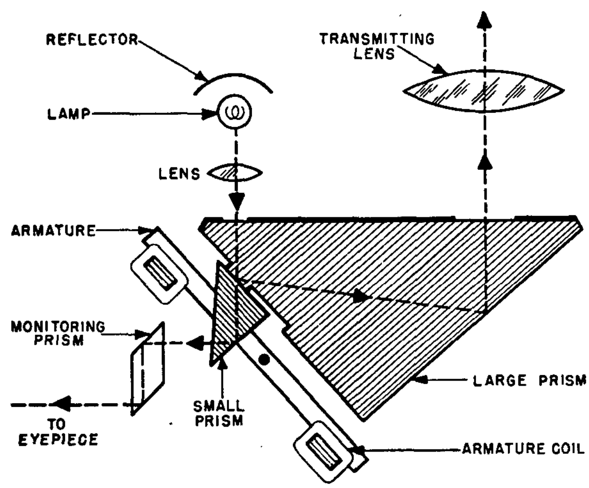


Figure 5. Modulation system in Lichtsprecher 80 (Zeiss).

These three systems are marked by great elegance of design and by optical precision and sturdiness of construction. The transmitter arrangement used in the earliest, the Li 80, designed before 1934, is so unusual that a diagram is shown in Figure 5. Although it uses a vibrating mirror, it works on quite a different optical principle from that described above. There are no grids. At a point where the radiation beam is undergoing total internal reflection in a large prism it is modulated by the mechanical oscillation of a glass surface (the small prism on the armature in the diagram) in the air *behind* the reflecting surface! The two surfaces are about $\frac{1}{7}$ of a wavelength apart (0.15 μ); the effect results from the penetration of the light energy across this gap even at an angle of total reflection. More or less of the light passes into the second glass and so out of the totally reflected beam, according as the second surface is nearer or farther away.

The other two Lichtsprechers are more normal

[d] A PbS cell is now being considered for daylight operation of this system. The system was to have been tested at BuShips test station on November 26, 1945, but due to the decommissioning of the USS *Marnell* these tests were delayed. This information is supplied by courtesy of Section 660E, BuShips.

vibrating-mirror galvanometer systems, although great ingenuity is again shown in the grid design. The grid lines are not opaque but are thin glass prisms so that instead of an average grid transmission of 25 per cent, as in the simplest vibrating-mirror system outlined above, the transmission is always 100 per cent (except for reflection losses). The modulation is accomplished by the diversion of more or less light out of the central beam into two side beams as the mirror vibrates and changes the fraction passing through different prism combinations. The effective width of the beam is thus tripled and the central intensity is doubled over that obtainable if the grids were opaque.

4.3.2 Portable, Hand-Held, Infrared Optical Telephone, Type W

Description and Performance

A major simplification has been achieved in an American vibrating-mirror system which conserves light by replacing all lenses by large-aperture concave mirrors and which eliminates the second grid by placing one grid on a parabolic surface and using it twice, once in transmission and once in reflection. This is type W, employing the so-called "reflex-image optical modulation system" which was developed under NDRC.[12]

Course of Development. The original development, initiated by Section 16.5 under Contract OEMsr–1073 with the University of California in 1943, led to a reflex-image system capable of voice-modulating the radiation (nonvisible ultraviolet) from a carbon arc drawing several kilowatts. When it was realized that the same principle would lend itself to a small lightweight unit as well, two portable hand-held instruments were designed and constructed.

Tungsten-filament lamps (infrared) were used as a matter of convenience in early tests. The results proved so promising that it was decided by agreement between Sections 16.5 and 16.4 to place major emphasis on the further practical development of such a portable system utilizing NIR radiation.

This development was carried out under Project Control AC–226.03 at the request of the Army Air Forces to provide the ground unit of an infrared plane-to-ground communication system with a desired ACW range of 3 miles, and under Project Control NS–371, at the request of the Bureau of Ships, to provide a system for two-way, day or night communication between amphibious craft at ranges up to 2 miles.

The electrically modulated plane unit (P–G system) of the plane-to-ground system was already under development by Northwestern University under Contract OEMsr–990 and will be described, together with the relationship of the two units, in Section 4.4.3. Type W may also be used for the plane unit of the plane-to-ground system.

It was requested that the ground unit have an NVR of 50 feet, weigh less than 40 pounds so that it could be carried to earth on the person of a paratrooper, have a self-contained power supply with an operating life of at least 15 minutes, be subsequently operable from a plane or car storage battery, and have hpi and hpr angles of 8 ± 2 degrees and 10 degrees, respectively (see Section 4.4.3).

Five separate units were constructed during the infrared type W development, of which the last two have the highest power (100 watts) and appear to work most successfully. Since the modulation method is independent of the source used, the system may be employed for either the UV or NIR and can probably be adapted to take interchangeable sources and cells for these regions. It can also be used in the visible and has the best transmitter so far developed for the IIR (see Section 4.8).

Only the infrared type W system is described in this chapter, since the ultraviolet work of the University of California is reported in Chapter 6 of the final report, Section 16.5. (See STR of Division 16, Volume 4.) This performance of two similar type W systems communicating to each other will be discussed in the present section. Their use as ground units to communicate with cesium lamp airborne units in the P–G system is described in Section 4.4.3. Much of the operational data on type W performance was obtained from the tests reported there on the third unit constructed. The termination of the war prevented any extensive tests under NDRC on the two final units.

General Design. An assembled and a disassembled transceiver of the final model are shown in Figure 6. The filter shown over the receiver in Figures 6 and 8 is not necessary for night operation and could be replaced by clear glass.

Each transceiver contains (1) a mechanical-optical reflex modulator, (2) a photodetector and

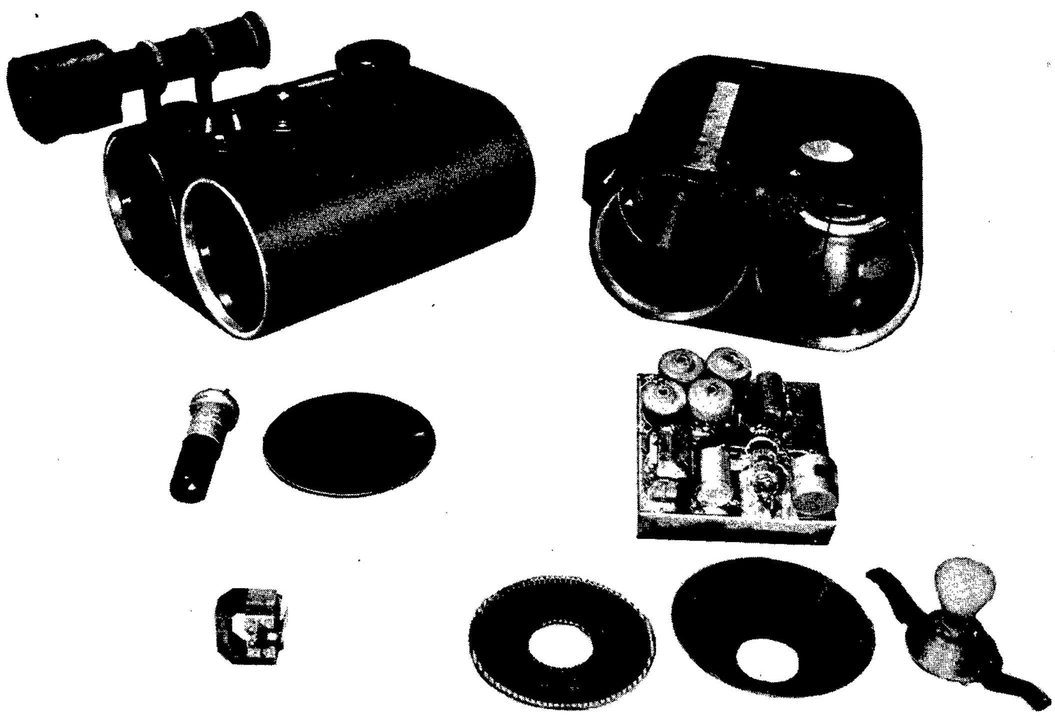


FIGURE 6. Assembled and disassembled type W transceiver.

receiver mirror, (3) a combined transmitter and receiver amplifier, (4) a microphone and earphone, and (5) an infrared metascope for sighting.

The transmitter, the optical components of which are sketched in Figure 7, modulates the steady

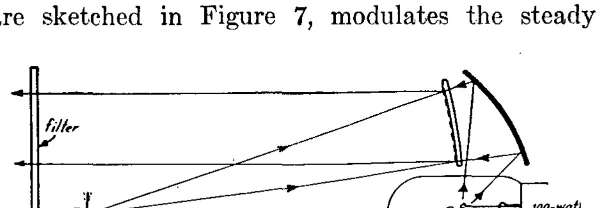


FIGURE 7. Type W transmitter design.

radiation emitted by a special 100-watt, tungsten filament lamp operated at a color temperature of about 3400 K. The radiation is focused by a gold-plated ellipsoidal mirror, 4.5 inches in diameter, onto an electrically driven concave vibrating mirror, $\frac{9}{16}$x$\frac{3}{4}$-inch oval, radius of curvature $5\frac{7}{8}$ inches, after passing through a concave parabolic grid mirror, 4.25 inches in diameter, which has its focus at the surface of the small vibrating mirror. The grid mirror, each side of which has a radius of curvature of $11\frac{3}{4}$ inches, is coated with reflecting strips of gold, approximately $\frac{1}{16}$ inch wide, alternated with clear spaces of exactly equal width. The vibrating mirror focuses an image of the grid back on the surface of the grid mirror, and the image of the filament on the vibrating mirror acts as a source of variable intensity. The grid mirror collimates this radiation into a 4x5-degree beam in which the variations in intensity are produced through the changes in the amount of radiation reflected from the grid mirror as the image of the grid is vibrated back and forth across its surface. A Lucite beam-spreader plate containing a number of little lenses may be

used to enlarge the transmitted beam to 10x12 degrees if desired. The modulator power required is about 0.1 watt.

The receiver uses a type A TF cell (Chapter 3) in a 4¾-inch diameter, 3-inch focal-length mirror to give a field of view of about 10x10 degrees. It has a four-stage amplifier which may be operated from a vibrator power pack or preferably from a light-weight 90-volt B battery.

FIGURE 8. Carrying and operating type W.

The transceiver head is about 5x10x12 inches in size and has a carbon microphone and an earphone built into its left side so that it may be held on the right shoulder in communication position and guided by one hand, as shown in Figure 8. For sighting on the distant station, a type AM phosphor metascope viewing tube is attached, though it appears that the somewhat heavier type C_4 infrared electron telescope will be required for sighting at the ultimate ranges. Arrangements are provided for the use of noise-canceling lip microphones and helmet headsets in noisy locations or for remote operation from an auxiliary phone on a long extension if desired.

One complete transceiver weighs about 8 pounds. The power pack containing a 6-volt, 25-ampere-hour storage battery and a small 90-volt B battery, weighs approximately 10 pounds (several pounds more if an electron telescope is used) and is carried by a strap over the shoulder. This supply will operate the 100-watt lamp for about 1 hour.

The units are reasonably rugged although the rather critical vibrating-mirror setting in the laboratory models is not so stable as it should be for field operation. The units can be made fairly watertight. No high-precision optical parts are used and all radio parts are standard production types.

Security. An Ohio State University [OSU] filter (Chapter 2) or a Polaroid XR3X-type filter with a K_p850 value (see Chapter 2) of about 0.30 may be used over the transmitter. The NVR appears to be about 2 per cent of the range, or about 100 yards for the 5-degree beam and 50 yards for the 10-degree beam.

The maximum ACW range of detection of the type W transmitter by a type C_4 image tube is estimated, from image tube experience with other transmitters, to be of the order of 6 miles.

Range. The final model type W systems have not been field-tested, but the ranges from one to the other of them may be computed from laboratory data and from measurements on other similar systems. An ACW night range of 3 miles is expected with the 4x5-degree beam, and of about 1½ miles with the 10x12-degree beam. Expected ranges to the P–G unit are given in Section 4.4.3; to type E, under the heading "Mixed Use" in Section 4.1.2.

Evaluation. The type W system is simple, versatile, and cleverly designed and has approximately the performance requested for it. If necessary the NVR can be brought down to the 50 feet requested in Project Control AC–226.03 by a suitable filter, probably with little loss in communication range. It, or some closely related system, ought to be considered for use as a general supplement to handy-talkie and walkie-talkie radio sets in close military operations.

Transmitter

Construction of Elements. Ordinary 40-watt bulbs were used in the first three units. For the last two models special 100-watt bulbs were made by the General Electric Company. A burned-out lamp can be replaced in 1 minute.

The magnification of the ellipsoidal mirror varies from 5$\times$ at the center to 3$\times$ at the edge, so that the surface of the vibrating mirror is rather uniformly covered by the diffuse image of the filament. None of the mirrors requires great accuracy of shape.

The grid was constructed on the parabolic glass plate by evaporation of gold through a metal pattern until an opaque layer was obtained. The width of the lines is $\frac{1}{16}$ inch, which is small enough to permit full modulation by the mirror galvanometer, but not so small as to impose stringent optical conditions on the concave vibrating mirror which forms the grid images.

The vibrating mirror is concave spherical so that it forms sharp images of the grid lines by reflection back on the parabolic grid surface. The image strips should overlap the actual strips by one-half their width when the galvanometer mirror is at rest. As the latter mirror vibrates, more light is reflected from the parabolic strips when it swings to one side and less when it swings to the other. For maximum modulation the image strips have an amplitude (displacement from rest position) of one-half their width. Overmodulation produces great distortion.

In these models strong overmodulation or mechanical shock may produce permanent displacement of the vibrating mirror from its rest position. To restore intelligibility, the parabolic mirror can be displaced laterally by an external eccentric pin until the grids and their images are again in the correct relation. A viewing port permits observation of them during this operation.

Vibrating-Mirror Element. The vibrating-mirror element finally adopted was modeled after the one developed and used by RCA in its moving-picture sound-recording system. A schematic diagram is given in Figure 9. A soft iron reed R vibrates back and forth in the field of a permanent Alnico magnet P, as the reed is magnetized in one direction or the other by the current in the voice coil C. The reed is 0.020 inch thick and $\frac{3}{8} \times 1\frac{1}{16}$ inch in area. It is clamped at the bottom between German silver blocks and clears the outer pole pieces in the neutral position by 0.005 inch. The end of the reed presses the mirror block M against a 0.002-inch thick phosphor-bronze tape T, and motion of the reed rocks the block back and forth on this tape. The concave mirror has a radius of curvature of $5\frac{7}{8}$ inches and is of oval shape, $\frac{9}{16} \times \frac{3}{4}$ inch in area. The voice coil impedance is about 100 ohms at 1,000 cycles.

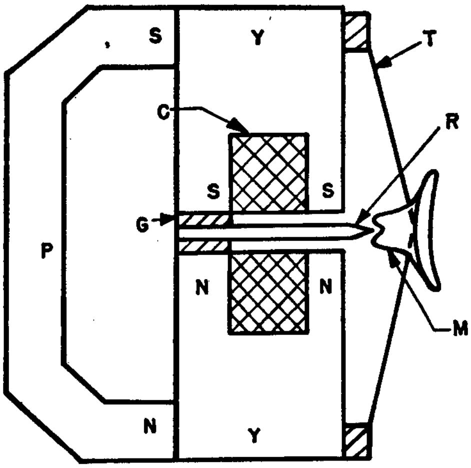


Figure 9. Type W vibrating-mirror galvanometer element.

Amplifier. The transmitter-amplifier is composed of the last two stages of the four-tube receiver-amplifier, Figure 10. A press-to-talk button throws a relay connecting the microphone transformer to the grid of the third tube and switching the output transformer from the earphones to the vibrating-mirror element.

A low-pass filter network flattens out the response curve of the vibrating-mirror unit, which peaks at 3,000 cycles per second. Low transmitter frequencies are cut out by a coupling condenser between the two tubes. The result is an overall transmitter and receiver response almost constant from 300 to 2,600 cycles. A volume control between the two tubes controls the transmitter modulation and is accessible by opening the case.

Receiver

Commercial Cetron tubes and photomultiplier tubes were tried at first. The latter were less suitable because of the weight of the required 1,000-volt supply. Maximum ranges of about 1 mile were obtained with the Cetron tubes in the first two units constructed, but this range was greatly reduced because of leakage across the tube if the

humidity was high. When the change to TF cells was made, on recommendation of the NDRC contractor, these difficulties were resolved and a gain in sensitivity of 20 to 30 decibels was realized, increasing the ACW range of the same units to about 3 miles.

The TF cell is placed beyond the focus of the mirror so that the light from a distant source is spread on a disk ½ inch in diameter. This smooths the irregularities which would be present in the directivity pattern if the light were focused to a sharp image on the grid structure of the cell.

Amplifier. The receiver-amplifier (Figure 10) is a conventional four-tube high-gain audio amplifier, containing some compensation for the decrease in TF-cell response at high frequencies.

Cathode bias is used on the tubes to simplify replacement. Between the first two tubes and the last two tubes is a decoupling filter in the plate and screen supply. Wire-wound resistors are recommended for low noise in the phototube and in the grid circuit of the first tube.

The receiver volume control follows the second stage of amplification and is cut out when the push-to-talk relay is in the send position.

The receiver draws about 0.7 ampere from the 6-volt storage battery and 5 milliamperes from the 90-volt B battery. The latter consists of cells from commercial batteries with a total weight of about 15 ounces. Use of cells from a new kind of battery now available would reduce the weight to 6 ounces. Vibrator power packs constructed for early tests weighed 30 ounces. Such packs are noisy, reducing ultimate receiver sensitivity, but they make the equipment independent of dry-battery replacement in field use.

Operational Tests

During the type W development many range tests were made on Berkeley Pier, 3.5 miles long, in San Francisco Bay. Field tests of the two first units, which employed 40-watt lamps (2x3-degree transmitted beam) and phototube detectors, were also made at night at the BuShips test station at Fort Miles, Cape Henlopen, Delaware, in March 1945. One unit was on the USS *Marnell*, the other on a

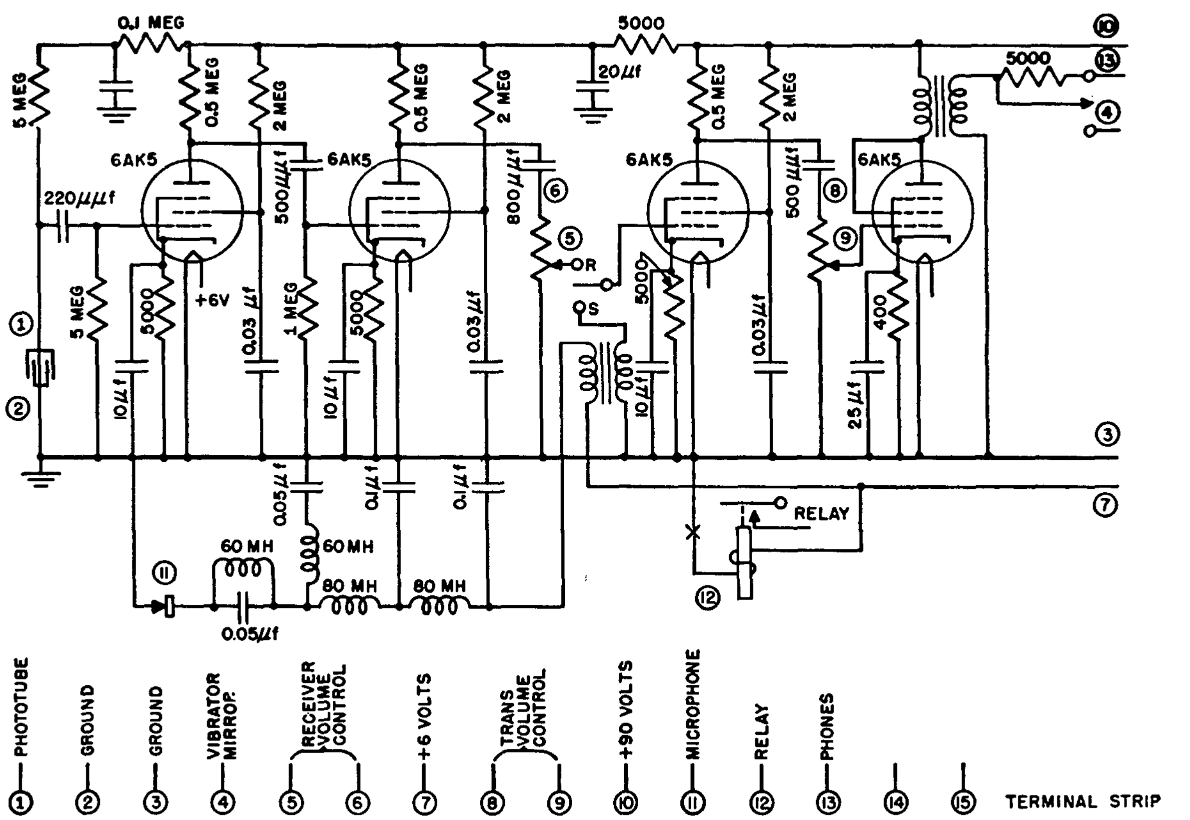


Figure 10. Type W transmitter-receiver amplifier.

motor launch. The initial limiting range was 2,600 yards, but this decreased steadily as phototube leakage developed because of high humidity.

After installation of TF-cell receivers in these units and construction of a third and improved unit, tests on Berkeley Pier gave night operational ranges of 2 to 3 miles with the 2x3-degree transmitted beam angle. One plane-to-ground test between two of these units in the summer of 1945 at Mills Field, Army Air Base, San Francisco, was unsatisfactory because of heavy airport traffic and unusually rough air and probably also because the beam angle used was only 5 degrees, too narrow for maintaining easy alignment with a hand-held unit. The noise-canceling lip microphone used was successful in eliminating transmission of background motor noise. The large effect of the backscattered radiation from the transmitter on this test dictated the installation of a press-to-talk button on the next two units constructed.

Because of the termination of World War II no further field tests have as yet been made for communication between naval craft.

Operational tests from the third type W unit to the P–G system are reported in "Operational Tests" in Section 4.4.3.

The ranges previously given above under "Range" for the fourth and fifth units built were computed from laboratory measurements.

Present Status

One of the last three units constructed has been allocated to the Special Projects Laboratory at Wright Field for plane-to-ground tests. The first of these tests is reported in Section 4.4.3. It is expected that these tests and any attendant modifications of the units will be carried out in consultation with Northwestern University workers under Navy Contract NObs–28373 which is continuing the work begun under Contract OEMsr–990. The other two of the last three units are to be allocated to the Navy for ship-to-ship, ship-to-shore, and finally plane-to-plane tests.

It is assumed that if these tests are up to expectations, either the Navy or the Air Forces may institute some commercial production program.

Recommendations

The system appears to have the military characteristics and performance requested for it as nearly as may be obtained in a laboratory model. The instability of the vibrating mirror constitutes a difficulty in the use of the present units. Whether still more source power is needed to meet the specifications of Project Control AC–226.03 can be determined only after further operational tests.

It is not certain that the best combination of source, operating temperature, and infrared-transmitting filter is being used in the present units. This point merits further study. Volume compression to increase the modulation and a speech-scrambler to increase the security could be installed with little increase in weight. It should be emphasized that lamps of much higher power can be used with this kind of system to give much greater range with *no* increase in weight except for the power supply. A narrower frequency pass band might give an increased range with the present units.

The type W system, without any major changes, would appear to be a very valuable and very secure supplement to portable radios for short-range military uses of all kinds. It has the best transmitter that has so far been designed for use in the IIR (Section 4.8).

4.4 ELECTRICALLY MODULATED ARC SYSTEMS

4.4.1 Systems Not Developed under NDRC

Systems for electrical modulation of a radiation source have previously not been able to compete very successfully with mechanical modulation of the emergent beam in such fields, for example, as sound motion pictures. This has been due, no doubt, to the lack of suitable gaseous discharge sources which can be efficiently modulated electrically. The carbon arcs used in the early Thirring system are noisy, have a low modulation ratio, and do not make a very steady or convenient source for field use.[e] However, in the last few years, electrically modulated radiation sources suitable for infrared communication have been produced in this country, France, and Germany, and have been used for military purposes. A French system using a xenon source will be described in Section 4.5.3. The German source is an r-f modulated mercury vapor lamp for infrared, but no further details are available.

[e] See work of Contract OEMsr–1073, reported in the Summary Technical Report of Division 16, Volume 4.

Two American electrically modulated infrared sources are now available: the "concentrated arc," and the cesium vapor arc lamp (Chapter 1).

Western Union Aural Signal Unit

The 2-watt concentrated arc is used in the battery-operated aural signal unit developed by the Western Union Telegraph Company for the Army Signal Corps. The unit has a cesium phototube receiver, beam widths about 1 degree or less, and a voice range of the order of 2 miles. It will not be described here since it was not an NDRC development.

Most of the further work on incorporating these two American electrically modulated sources into complete voice communication systems has been carried out by Northwestern University under Contract OEMsr-990. Complete systems have been built using the first source, and later the second, in developing the so-called type E system for ship-to-ship communication (Section 4.4.2). Subsequently, this contract devised a third and a fourth system, employing the cesium vapor lamp, for aircraft communication (Sections 4.4.3 and 4.4.4). These four systems will now be described.

4.4.2 Ship-to-Ship Communication System Type E

Description and Performance

Course of Development. The type E system was developed under Contract OEMsr-990 (Project Control NS-159). The equipment as originally requested was to have angles of 15 to 40 degrees for secret communication at night in a convoy between one ship and several others simultaneously. When the development was initiated in May 1943, the intention was to maintain alignment of the transceivers during communication by an automatic tracking arrangement; but this was found to be unnecessary since the beam angles of about 15 degrees in the system as developed were sufficient for manual guiding of the heads, even on a destroyer in a fairly heavy sea. Voice and code ACW ranges of 5 miles were desired; these values were exceeded with the system developed.

The type E system, as finally put into production, is somewhat more elaborate than the laboratory model shown in Figure 11. It consists of (1) two cesium-lamp sources and reflectors, (2) two TF-cell detectors and reflectors, (3) port and starboard transceiver heads (Figures 12 and 15), each containing a source, receiver, reflectors, starting transformers, receiver preamplifier, and an electron telescope for sighting, (4) two deck pedestals and gimbals (Figure 15) for manual guiding of the heads (total weight of each pedestal, assembled, nearly 200 pounds), (5) a starting circuit for the source, (6) a microphone and power amplifier for voice-modulating the source, (7) a key and 1,500-cycle oscillator for sending code, (8) receiver amplifiers, headphones, and loud-speaker, and (9) a control panel installed below decks (500 to 600 pounds), containing items 5, 6, 7, and 8 (Figure 16).

The development may be divided into three stages. In the first stage, a 100- to 150-watt concentrated arc was used as the source and a gas-filled Cs-Ag-O surface phototube (Chapter 3) as the photodetector. In the second stage a great improvement in range was obtained by replacing the phototube with a Cashman TF cell developed by Northwestern University Contract OEMsr-235 (Chapter 3) and by replacing the concentrated arc by the cesium-vapor lamp. The resulting system will be called here the laboratory model type E system. In the third stage, workers under Contract OEMsr-990 carried on consultation service for two manufacturers, Belmont Radio Corporation and Cover-Dual Signal Systems, Inc., Chicago, Illinois, engaged in adapting this system to quantity commercial production for the Navy. The latter stage was not part of the NDRC development and will not be described except in summary. Details of the consultation will be found elsewhere.[19,20,21]

Several reports have been written covering the laboratory development of type E.[13-18] The last one contains in addition extensive data on the electrical and radiation characteristics and operating lives of the sources, comparisons of different types of photodetectors and the theory of detector cell noise, studies of filters, and a discussion of ranges obtainable with different values of beam width and source power.

Laboratory Model. The successful laboratory model of the type E system is shown schematically in Figure 11. The system comprises a transceiver head on gimbals, a receiver-amplifier and power supply, and a main control panel.

The transceiver head is shown in Figure 12 with the transmitter directly below the receiver. The filter has been removed to show the source, which

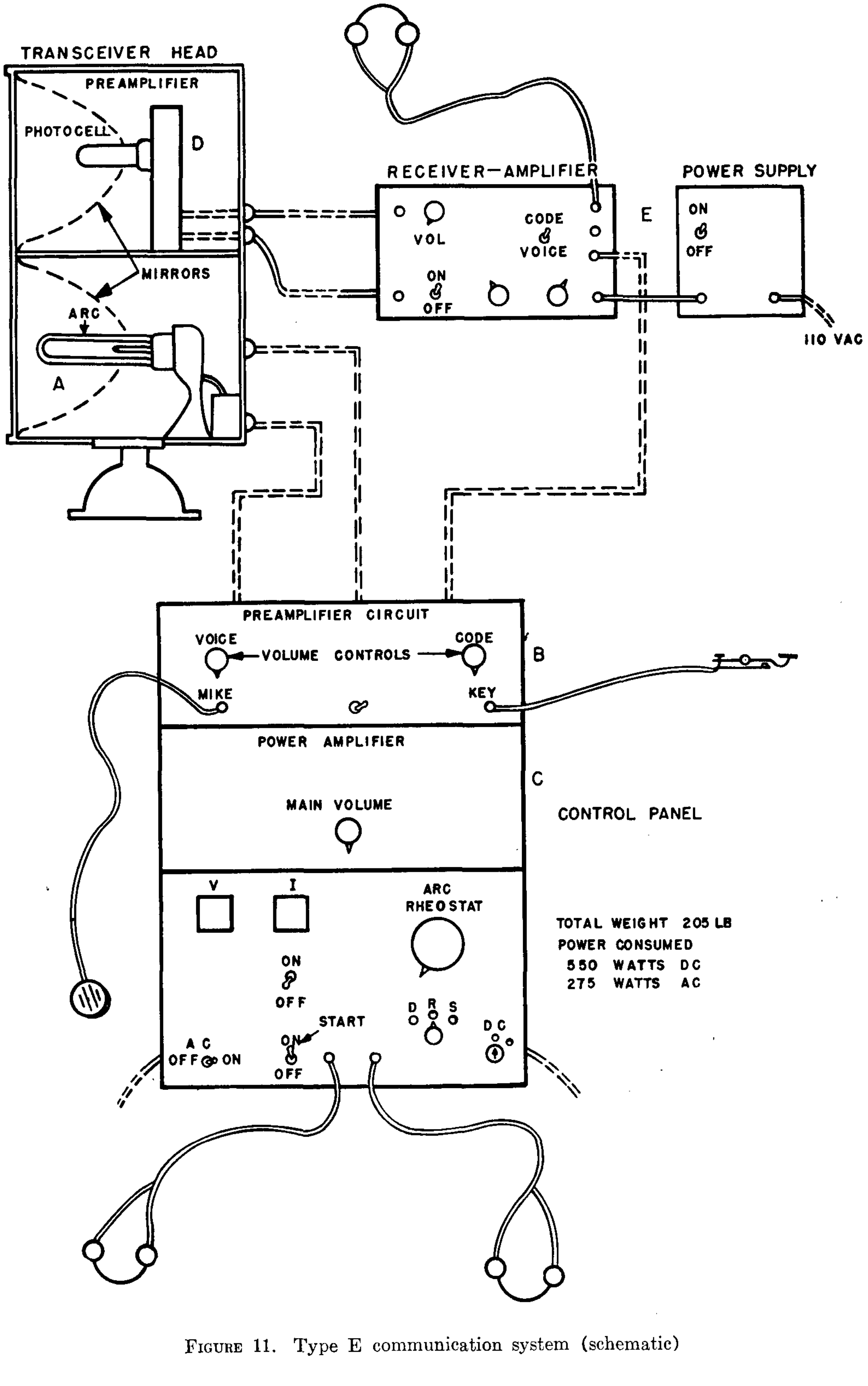


FIGURE 11. Type E communication system (schematic)

is a 90-watt cesium vapor lamp mounted axially at the focus of a 14-inch diameter, 1¾-inch focal length, Alzak aluminum parabolic reflector. Most of the communication is carried by the two cesium

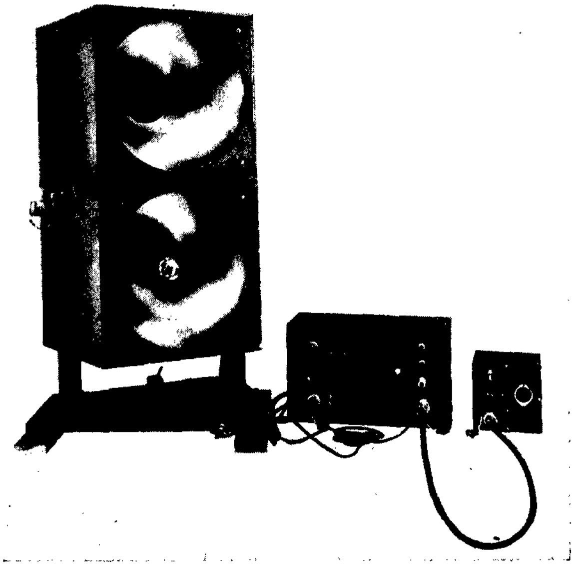


Figure 12. Type E transceiver head, laboratory model.

resonance lines 0.8521 and 0.8944 μ. The hpi width of the emergent beam is about 13 degrees (Figure 13) and the optics factor is about 40×. The transformers for heating the lamp filaments are mounted behind the mirror.

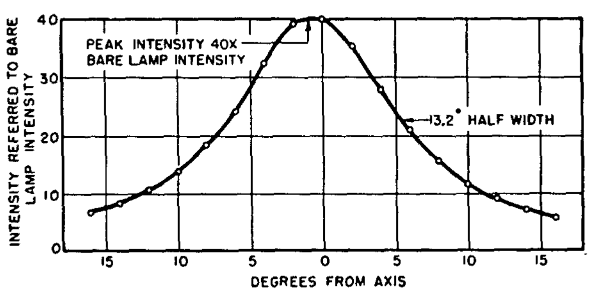


Figure 13. Type E cesium lamp transmitter intensity distribution.

The photodetector cell is a type B TF cell (Section 3.3.2) mounted axially at the focus of an identical reflector. The hpr width is from 18 to 19 degrees (Figure 14, curve A) and the optics factor is about 40×. The cell is set in a socket in the cathode-follower preamplifier which is directly behind the mirror.

The laboratory model transceiver head has dimensions of about 16x16x32 inches and weighs about 60 pounds when mounted on gimbals for manual operation. The transmitter and receiver are separately shielded with sheet aluminum. The head is provided with a clamp for attaching a type C_3 infrared electron telescope for sighting purposes.

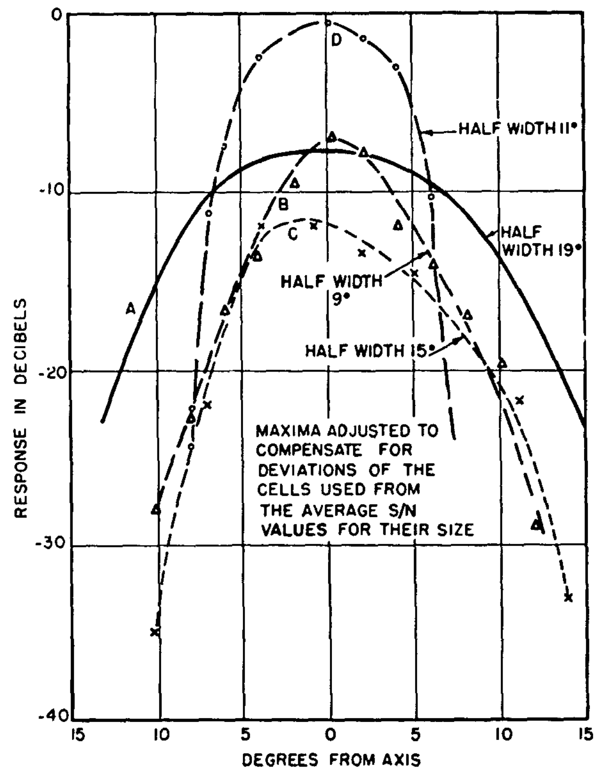


Figure 14. Directivity patterns for various cell and mirror combinations.

In this model short cables lead from the transceiver head to the receiver-amplifier (Figure 11). This amplifier has voice and code pass bands which peak at about 1,500 cycles per second; the voice bandwidth is about 600 cycles per second, and the code band can be adjusted to a width of between 10 and 200 cycles per second, just great enough to prevent the circuit from breaking into self-oscillation. The voltage gain of the amplifier is about 95 db on voice and 120 db on code. The receiver power supply and amplifier together weigh about 15 pounds. Earphones are provided so that the man guiding the transceiver head and operating the receiver may monitor the conversation.

Longer cables connect the transceiver head and receiver-amplifier to the control panel, which con-

tains circuits for starting, d-c operation, and voice or code modulation of the cesium lamp. The panel will control and fully modulate either concentrated arc or cesium vapor lamps in the d-c power range between 75 and 150 watts. Modulators for lamp

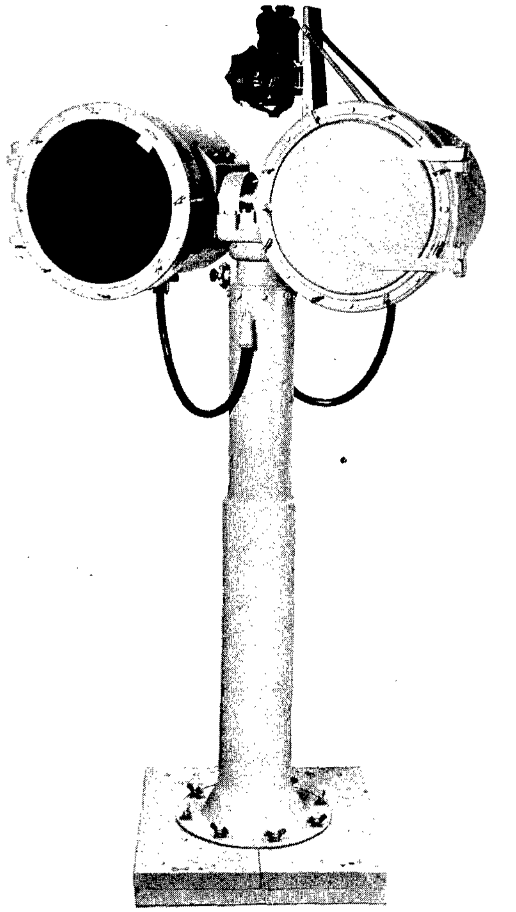


FIGURE 15. Belmont Radio Corporation US/E-2 Nancy pedestal and transceiver head.

sizes from 2 to 1,500 watts were also constructed during the development of type E. In order to increase the average speech modulation, the pre-amplifier has a volume compressor and a high-pass wave filter which cuts out frequencies below 1,000 cycles. A send-receive switch is included which reduces the cesium lamp current to about 1 ampere in the receive position and at the same time introduces a wave filter in order to reduce the interference due to radiation from the source back-scattered by the atmosphere into the receiver.

The control panel is in a drip-proof case of dimensions about 12x18x24 inches and weighs about 130 pounds.

Noise-canceling dynamic microphones and crystal-type headsets are used.

The power consumed by the whole system is about 550 watts from a ship's 110-volt d-c supply, of which about 450 watts is dissipated in lamp ballast, and about 275 from the 110-volt 60-cycle supply.

Production Models. The two models placed in quantity production by the Navy are very similar in their overall design to the laboratory model. Each has two transceiver heads (port and starboard), with provision for modulating the source in one of them at a time and for receiving from one or both.

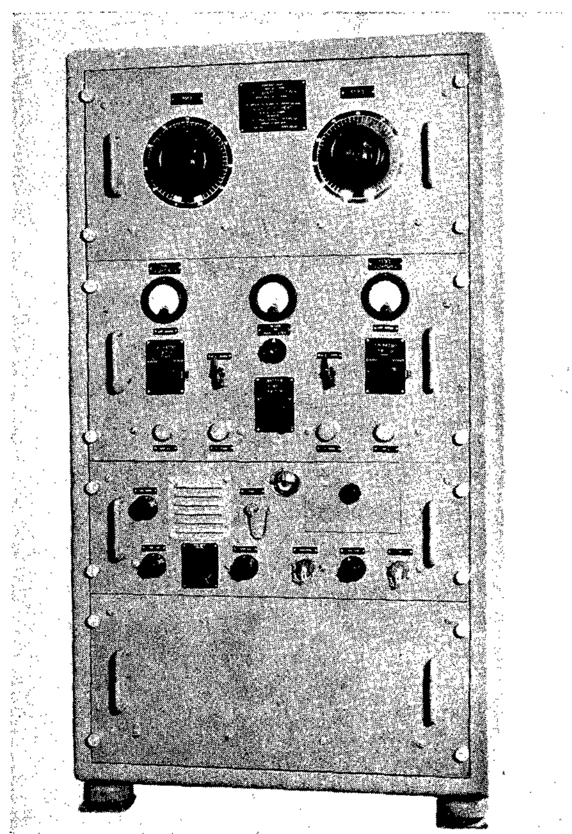


FIGURE 16. Prototype US/E-1 control panel with Cover-Dual signal systems incorporated.

A Belmont Corporation pedestal and head is shown in Figure 15. The remainder of the electronic equipment is all in the control panel which is installed below decks. A control panel made by Cover-Dual is shown in Figure 16.

The approximate weights of these systems were

given above under "Course of Development." The total power consumption of each system is about 700 watts (about 600 dissipated in lamp ballast) from the 110-volt d-c ship supply plus about 400 watts from the 110-volt 60-cycle supply.

Security. The XRN5PX PVA sandwich-type Polaroid filters and the OSU resin plastic filters made on white glass may be equally satisfactory. Extensive comparative measurements have been made on various filters to be used with the type E system, but no complete agreement about the absolute scale of the range measurements has been obtained. However, it appears that in order to restrict the NVR to 400 yards, as desired for type E by the Navy, these filters must have ehT values for the cesium source of between 0.6 and 0.8. The maximum range of detection of the transmitter by various foreign and American, type C_3 and C_4, infrared electron telescopes has been tested and is of the order of the code range of the system.[22] This large range is of course necessary for manual guiding of the transceiver heads.

Range. The range of type E is rather accurately known from numerous field tests. The vacuum voice range of both the laboratory model and the production prototype models is about 30 sea miles, ACW range 6.5 sea miles. Code ranges are more uncertain, as they depend on the sharpness and tuning of the receiver band, but the indicated vacuum range is about 100 miles, ACW range about 9 sea miles.

The voice-range directivity pattern in various kinds of weather is shown in Figure 17. The area enclosed by the curves is the area within which one ship can carry on simultaneous two-way communication with several other ships.

Evaluation. The type E system is comparatively easy to detect with an electron telescope, and intelligence transmitted by it may be received with simple audio amplitude-modulation photoreceivers. This insecurity is a necessary consequence of the wide beam, the wavelength region used, and the simplicity of the modulation method and cannot be eliminated without going to an entirely different kind of system.

Considerable thought has been given to maximizing the performance of every component and the range of the type E system as a whole. Theoretical computations indicate that probably no other near infrared system, constructed with the same angles and power and present photodetector cells, can have more than about a mile additional ACW range.

Gunfire causes little harm to sentence intelligibility, but searchlights and starshells are troublesome. How much their effect can be reduced by filtering the receiver is unknown. Moonlight causes little trouble. The system was not designed for daylight

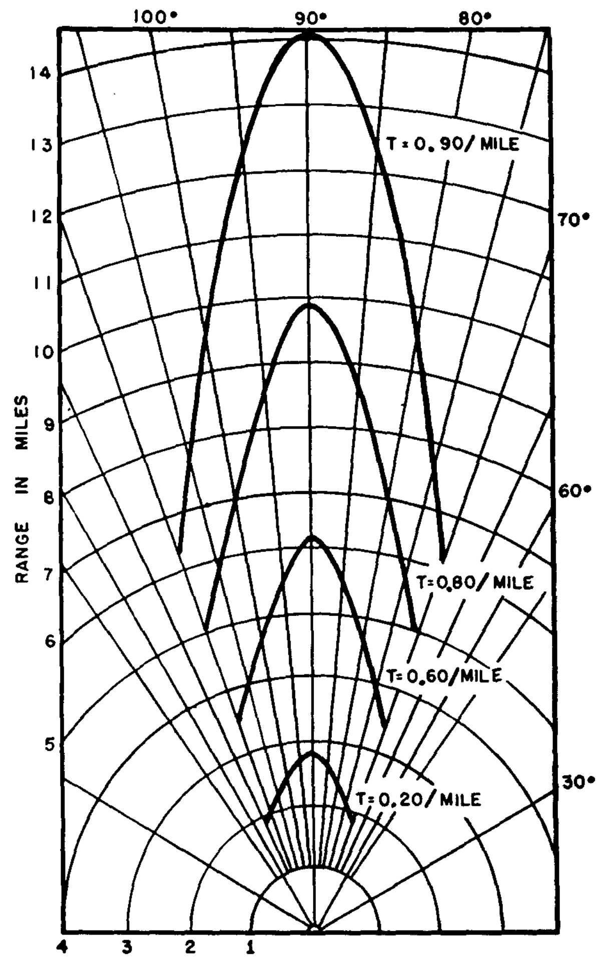


FIGURE 17. Area of two-way voice communication with fixed transceiver, type E.

communication but it might work in the daytime at medium ranges with filtered and shaded receivers and with minor changes in the preamplifier circuit or with the replacement of TF cells by PbS cells of the same size (see "Daylight Operation," Section 4.1.3).

Transmitter

Concentrated Arc Source. The concentrated arc source was used throughout the first stage of the development. Various sizes from 2 watts to 600 watts were studied, with the emphasis concentrated

on those in the 80- to 150-watt range. These studies were carried out by Northwestern University Contract OEMsr–990 in cooperation with Western Union Telegraph Company Contract OEMsr–984 which produced the lamps. Many different design changes were suggested by workers in both groups and were made by those working under Contract OEMsr–984 in an attempt to increase the stability, life, and output of modulated filtered radiation.

A typical 100-watt lamp has a voltage drop of about 16 volts at a current of 6 amperes, and an intensity of about 100 holocandlepower (hcp) measured on an RCA 919 phototube (Chapter 1). Since this is a cosine law source, the total flux is of the order of 300 hololumens. The lamp has a continuous spectrum peaking near 1 μ, similar to that of a high-temperature tungsten lamp.

The d-c or a-c variation of the radiant flux is very nearly linear with current, but not with voltage. The light-current modulation ratio depends somewhat on the filter used and a great deal on the frequency (Chapter 1) but is about 0.10 at 1,000 cycles per second with a Polaroid XR3X-41 filter. The ratio decreases at higher frequencies. Up to about 75 per cent current modulation can be used without serious distortion of the light wave. The arcs tend to be extinguished if the current drops to zero for a short time, as, for instance, by modulation near 100 per cent at frequencies below 1,000 cycles per second.

The apparent a-c impedance of the normal arc must be known in designing the transmitter amplifier; it is between 1.5 and 2 ohms at 1,000 cycles per second for the 100-watt arcs tested. The reactance component is about 0.5 ohm.

Cesium Vapor Lamp. In the final laboratory model of type E, the cesium vapor lamp was used. Models of this lamp, produced by Westinghouse Electric Company under a BuShips contract, first became available to Contract OEMsr–990 in August 1944. The 100-watt sizes proved to be similar in electrical characteristics to the 100-watt concentrated arcs and could be operated from the transmitters designed for the latter with only minor changes in these transmitters.

Some recommendations were made by those working under Contract OEMsr–990 as to the final design of a cesium lamp for the production type E equipment, based on the experience with early models. The resulting lamp is the 90-watt 5.5-ampere Westinghouse CL–2 cesium vapor lamp which has been described in Chapter 1.

A typical lamp has a voltage drop between 12 and 20 volts at the rated current, depending on its gas pressure and previous history. The intensity is about 100 to 150 hcp measured on an RCA 919 phototube. This is almost a line source so that the distribution follows the sine law, and the total flux is 1,000 to 1,500 hololumens. The lamp concentrates about 20 per cent of its input energy into the two cesium resonance lines, 0.8521 and 0.8944 μ. Very little of the radiation is in the "visible," so the infrared filters used need not be very dense.

The d-c or a-c variation of the radiant flux is again nearly linear with current. The light-current modulation ratio is 0.90 to 1.00, independent of the infrared filter used and of the frequency, up to 5,000 cycles per second. Over 90 per cent current modulation may be used without serious distortion. The lamp does not extinguish with 100 per cent modulation, even at 60 cycles per second.

The a-c impedance at 1,500 cycles per second is between 1 and 2 ohms. The reactance is about 0.5 ohm.

The cesium lamps differ from the concentrated arc lamps in requiring a warm-up period of about 15 minutes after starting before they attain full intensity.

These lamps have about three times as much hololuminous flux, about nine times as great a modulation ratio, and about twice as large an ehT (for filters giving a 400-yard visual range with the transmitters to be described) as a concentrated arc lamp of comparable wattage. The useful modulated and filtered infrared radiant flux from the cesium lamps is thus greater by a factor of about 50. Optical systems to produce beams about 20 degrees wide are harder to design with high efficiency for these lamps than for the concentrated arc, so that the useful gain in practice is by a factor of about 20 for phototubes and about 10 for TF cells, the longer wavelength response of which favors their use in the concentrated arc lamp.

Lamp Operation. Both sources may be operated from the 110-volt d-c ship supply, with suitable ballasting in series to limit the current to the proper value. Part of the ballast resistance is made variable for manual adjustment of the current to the proper value. Iron-wire ballast tubes could be used for automatic current regulation, except that none

of adequate power rating is commercially available.

Operation from a differentially compounded motor generator, of the type used for welding arcs, has also been considered. This would be more efficient, eliminating the loss of power in ballast resistors, but would complicate the equipment.

Whether the lamps are run from the ship supply or from a local generator they are modulated by the generator ripple. This may not interfere with speech modulation but may prove objectionable when a communication system is in the "receive" condition because of the noise in the receiver from the ripple in the backscattered radiation. If this is the case, the ripple may be eliminated by inserting L-C filtering in the d-c line.

Lamp Starting. Both sources are started by high-voltage breakdown of the discharge path. The discharge then maintains itself when they are switched to the low-voltage, high-current power source. Several methods of applying the high voltage were studied, including the use of a Tesla coil or vibrator-induction coil, which is fairly satisfactory for laboratory use.

The best starting method for the concentrated arc lamp in field operation is the use of a high-voltage rectifier with poor regulation. This provides a true arc of the desired polarity so that the switch-over to the low-voltage, high-current power source is very reliable. Even with this method several starts are often necessary before the arc strikes to the desired zirconium oxide cathode spot. An arc to any other spot is unstable and does not have the proper spectral distribution and modulation characteristics.

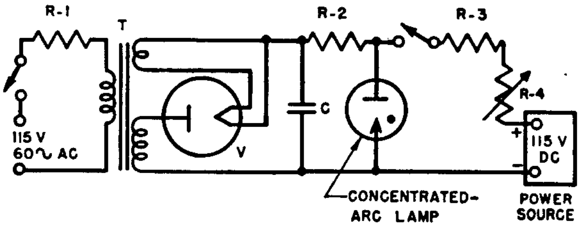


FIGURE 18. Typical high-voltage rectifier starting circuit for concentrated arc lamp.

A typical rectifier starting circuit is shown in Figure 18. The rectifier voltage builds up to about 4,000 volts d-c to insure breaking down the arc gap with every different type of concentrated arc. Either half-wave or full-wave rectification is satisfactory. In the final concentrated arc system, resistors R–1 and R–2 limit the starting current to about 150 ma. Since R–2 is large (about 2,500 ohms), it absorbs little power when the lamp is modulated.

During the development of type E, this same starting method was also used (associated with initial filament heating) for the cesium lamp, although it is said to shorten lamp life. A different method, recommended by the lamp manufacturer, was used for the cesium lamp in the commercial type E models. Still another method was employed in the aircraft systems (Sections 4.4.3 and 4.4.4).

Lamp Modulation. Both sources are modulated by a constant-current generator, as shown in Figure 19. The impedances of the d-c and starting circuits are kept high compared to the impedance presented by the lamp, so that they will absorb little of the modulator power.

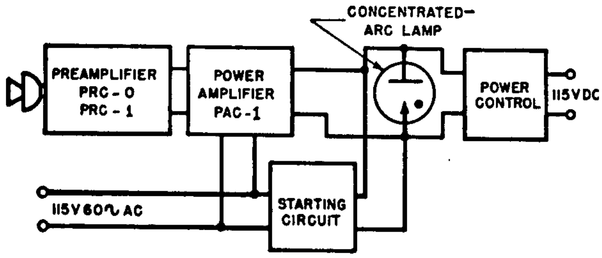


FIGURE 19. Block diagram of complete type E transmitter circuits.

For the 100-watt lamps of both kinds, pentode or zero-bias class B triode power amplifiers were used as modulators to provide an essentially constant-current source with high internal impedance and consequently good stability and linearity.

Efficient power transfer was secured by using a transformer to match load impedances; the modulation energy was delivered through an electrolytic blocking condenser.

The a-c volt-amperes required to modulate a lamp fully is approximately

$$VA = \frac{I^2 Z}{2},$$

where I is the d-c current and Z is the lamp impedance. A 5-ampere lamp with 2-ohm impedance thus requires about 25 volt-amperes from the power amplifier. When transmission, transformer, and shunt losses are considered, the required modulator power may be 50 watts for such a lamp.

The required modulator power for a cesium lamp may vary by 20 per cent, depending on the filament terminals to which the modulator is connected.

Amplification. Amplification of speech waves from microphone to the final modulator stage is obtained in a conventional manner. A high-pass filter, with cutoff at 1,000 cycles, and a volume compressor are used to increase the average modulation current.

A block diagram of the compressor circuit and a graph of typical performance are shown in Figure 20. It is estimated that the use of the compressor raises the weaker speech passages about 6 db for the same modulation of stronger passages. This is a considerable gain as it is the stronger passages, of course, which limit the allowable modulation.

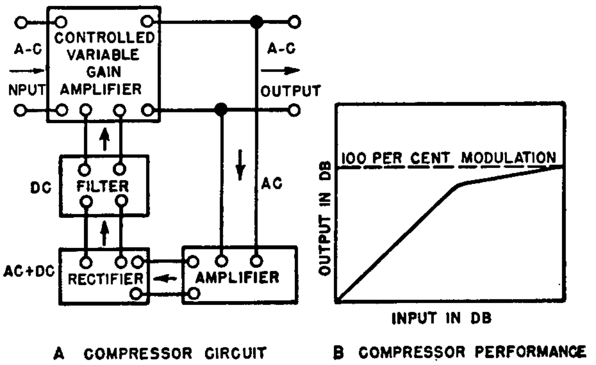


FIGURE 20. Block diagram of type E compressor circuit, and graph of typical performance.

To increase the modulation further, the higher speech frequencies are pre-emphasized by adjusting the modulator frequency response to increase at the rate of 4.5 db per octave. This compensates for the loss of amplitude in the higher human speech frequencies, so that all frequencies reach full modulation at about the same input signal level, and the total modulated radiant energy is brought to a maximum.

The introduction of compensation for the decrease of modulation ratio with increasing frequency in the concentrated arc was considered, but it was concluded that this would decrease the total modulated radiant energy.

Complete Transmitter Circuits. The block diagram in Figure 19 shows the functional arrangement of the transmitter units.

The preamplifier provides the necessary amplification of microphone signals, so that the power amplifier can fully modulate the lamp. The power amplifier contains all the wave filters, the volume compressor, and all frequency-response equalizing networks.

The power amplifier provides modulating current for the lamp. A commercial 60-watt public address unit which was readily available and adaptable to rack mounting was used on all modulators.

The starting circuit consists of a half-wave rectifier and filter, as already discussed.

The power-control unit contains all the arc ballasting resistors, switches, relays, and other required components for control of the system. All cables required to connect a complete control and modulator unit are brought to receptacles on this unit so that it serves to distribute all incoming and outgoing power.

Carbon microphones were used at first, but the batteries necessary to operate them were not suited for tests in freezing weather. Dynamic microphones were then tried but transmitted a great deal of disturbing ambient background noise in field operations. Finally, noise-canceling dynamic microphones were used and proved very satisfactory.

In the first preamplifier a clipper or peak limiter was put in to prevent extinguishing the concentrated arcs by overmodulation. This proved unnecessary in later circuits with better elimination of low frequencies.

For code operation a two-tube, resistance-capacitance tuned, amplitude-stabilized oscillator was incorporated in the preamplifier.

In the final volume compressor, a sharp turnover and relatively flat compression characteristic (Figure 20) are obtained by use of a cathode follower to stabilize the rectifier bias so that the bias is independent of the level of the rectified and filtered signal.

The final transmitter whose control panel is sketched in Figure 11 was capable of operating either a 100- to 150-watt concentrated arc or a 120-watt cesium lamp. Some improvements were made for use with the latter lamp. Filament preheating was provided. Duplex operation, which had previously been used, was found to be no longer satisfactory because of backscatter. Therefore, a send-receive switch was installed in the control panel. This de-energized the receiver output in the send position and inserted ballast resistance and capacitance in the lamp line in the receive position, so as

to reduce the lamp current to 1 ampere and filter it. Further improvements in the final control panel included extensive shielding of the transmitter circuits to prevent receiver-transmitter interaction.

Receiver

Photodetector Cells. Photodetector cells were chosen by several criteria. First, of course, high infrared sensitivity in microamperes per filtered hololumen was necessary. In order to obtain the large angles of view of 15 to 40 degrees desired for the equipment and still have a large enough mirror gathering area, large-area cells were needed (see Section 4.1.3). In the development of receivers, circuits were devised whose sensitivity was limited only by the shot noise or thermal dark noise in the detector cell itself, and therefore this cell noise had to be low compared to the sensitivity in order to give a large S/N ratio.

Two different types of photodetector cell met these requirements fairly well and were used successfully in receivers during the development of type E. These are the gas-filled Cs-Ag-O phototube (Chapter 3) which gave better results than vacuum phototubes. This tube was used in the first stage of of the development, the TF cell in the second.

The most satisfactory gas-filled Cs-Ag-O surface phototube which was commercially available for this work was the type CE–1–AB manufactured by the Continental Electric Company. It had a cylindrical cathode with a projected area of ⅝x1½ inches and a dark current of from 0.5×10^{-11} to 1.0×10^{-10} ampere. The sensitivity of these tubes was of the order of 250 to 450 μa per hololumen for a source having a color temperature of 2848 K, and their response for this source with a Polaroid XR7X25 filter interposed was 10 to 30 per cent of that with no filter.

Samples of several other types of gas-filled phototubes of various sizes were tested, including type CE–15 and CE–53 from Continental Electric Company and type PIT from Farnsworth Television Corporation Contract OEMsr–1094, but all had lower average infrared sensitivity or higher dark current than the CE–1–AB tubes. Several Farnsworth type 6PEA six-stage multiplier phototubes (Chapter 3) were also tested. Such photomultipliers introduce the problem of a high-voltage power supply but they simplify the auxiliary amplifier problem. These tubes were found to give infrared S/N ratios up to the values obtained with the CE–1–AB tubes, but the cathode area was smaller, entailing a reduced angle of view, and for this reason they were not used further in the development.

The Cashman TF cells were not used until the spring of 1944 as it was felt that they would not be suitable for voice reception on account of their well-known falling frequency response (Chapter 3). When it was realized that the noise falls with frequency at the same rate, so that the S/N ratios are the same at the important speech frequencies near 1,500 cycles per second as at low frequencies, TF cells were immediately tried as voice detectors and proved very satisfactory. Type A cells, of ¾x¾-inch sensitive area, were tried first, and gave S/N ratios with the concentrated arc covered with a Polaroid XR3X41 filter about as good as the best selected CE–1–AB gas-filled phototubes, which have somewhat greater area. Upon request of Northwestern Contract OEMsr–990, Contract OEMsr–235 then produced larger TF cells, later called type B, about 1¼x2 inches in sensitive area. Their sensitivities were almost equal to those of the smaller cells, and their larger size made it finally possible to obtain the large angles desired for the type E equipment, with mirrors of adequate size to give the desired range. Further discussion of these cells and their commercial manufacture is given in Chapter 3.

The modulated flux required for threshold speech intelligibility is some 6 db less for the best selected phototubes than for the best selected TF cells of comparable area, using a cesium lamp source and the type E voice circuits; no conclusions about relative performance under other conditions should be hastily drawn from this.[18] In spite of this poorer ultimate threshold, TF cells were chosen for type E because of several counterbalancing considerations: (1) The TF cells can be made more uniformly, so that their average performance seems to be better than the average phototube performance; (2) they can be made with larger areas than available phototubes of equal sensitivity, thus making feasible the large hpr angles desired for type E; (3) the TF cells are completely free from microphonics; (4) they are less sensitive to background light; and (5) their lower impedance level makes the problems of shielding and moisture less troublesome.

For successful operation of the gas-filled phototube, which has a high internal resistance, moisture problems become so serious that completely enclosed

desiccated preamplifiers are necessary. With TF cells, which have a much lower dark resistance—only 1 to 10 megohms—treatment of tube bases and sockets with a water repellent is sufficient to prevent loss of sensitivity due to moisture.

Preamplifier. A great number of preamplifier circuits and modifications were constructed for a-c and d-c operation both with phototubes and with TF cells. The final circuits have a sensitivity limited only by the noise level of the cell itself, and thus represent a many-fold gain in sensitivity over the conventional circuits which were tried initially. The original reports [18] give the details of these low-noise circuits and the effect of various factors on their sensitivity.

Early studies were made with d-c battery-operated phototube and TF-cell preamplifiers. The later and final laboratory preamplifier design for use with TF cells is a-c operated for convenience on shipboard. For reducing noise, the TF-cell load resistor is a wire-wound or equivalent low-noise composition resistor, and care is taken to minimize microphonics.

This preamplifier is essentially a cathode follower in which the cathode has been grounded to minimize any hum which might be introduced by heater cathode leakage or capacitance. The voltage supply is taken from the plate of the pentode and the circuit is designed to prevent overvoltage on the photocell.

Amplifier. The requirement of low noise in the amplifier is also stringent. The voice pass band must be restricted approximately to the region between 1,000 and 2,000 cycles and the code pass band made as narrow as possible to cut out unnecessary noise. Care must be taken in selecting components, in preventing coupling between various components, and in eliminating common ground leads between high- and low-level stages. Helpful suggestions about the design were contributed by University of Michigan Contract NDCrc-185.

Following early work with a d-c amplifier, the final four-stage a-c amplifier was constructed with the characteristics outlined above under "Laboratory Model." A narrow pass band bridge-T feedback amplifier for code has been incorporated in the main receiver-amplifier in such a way that it can also be used as the predominant factor in restricting the pass band in the voice position. A large fixed and a small variable resistor, in series with the choke in the bridge-T network, effectively lower its Q so that the bandwidth becomes 600 to 700 cycles. A switch shorts the fixed resistor for code reception, and the variable resistor is then adjusted to give the much narrower bandwidth desired for code. Trimmer condensers allow slight changes in the frequency for peak response. The frequency response of this amplifier for both voice and code is shown in Figure 21.

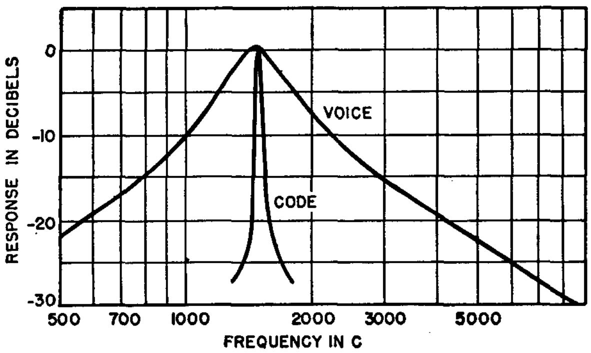


FIGURE 21. Frequency response on voice and code of type E a-c receiver-amplifier.

OPTICAL SYSTEMS

Point Source Transmitter. Many systems were tried for obtaining a wide uniform beam from a concentrated-arc source (first stage of development). In the best of these uniformity was obtained by use of spread lenses over a parallel beam formed by a parabolic mirror with the source at the focus. The most compact and efficient system of this type is represented in Figure 22 (T–3a). The source faces forward, that is, in the same direction as the emergent beam. It is placed at the focus of a "deep" parabola, the useful mirror surface of which is 6 inches in diameter and 7 inches long, with a focal length of about 0.6 inch. An $f/1.2$ plano-convex lens collects light that would otherwise pass uncollimated out the front opening of the mirror. An 18x8-degree spread lens was used to produce a divergent beam. The beam distribution is shown in Figure 23. The system had an optics factor of about 50$\times$ and efficiency of about 60 per cent.

Vapor Lamp Transmitter. The system chosen for use with the cesium-vapor lamp (second stage of development) has been described above under "Laboratory Model." It gave the best average intensity, throughout the central 20 degrees of beam width, of any of several different optical systems tried. The distribution from the transmitter is shown in Figure 13. The pattern has radial symmetry, with a half-

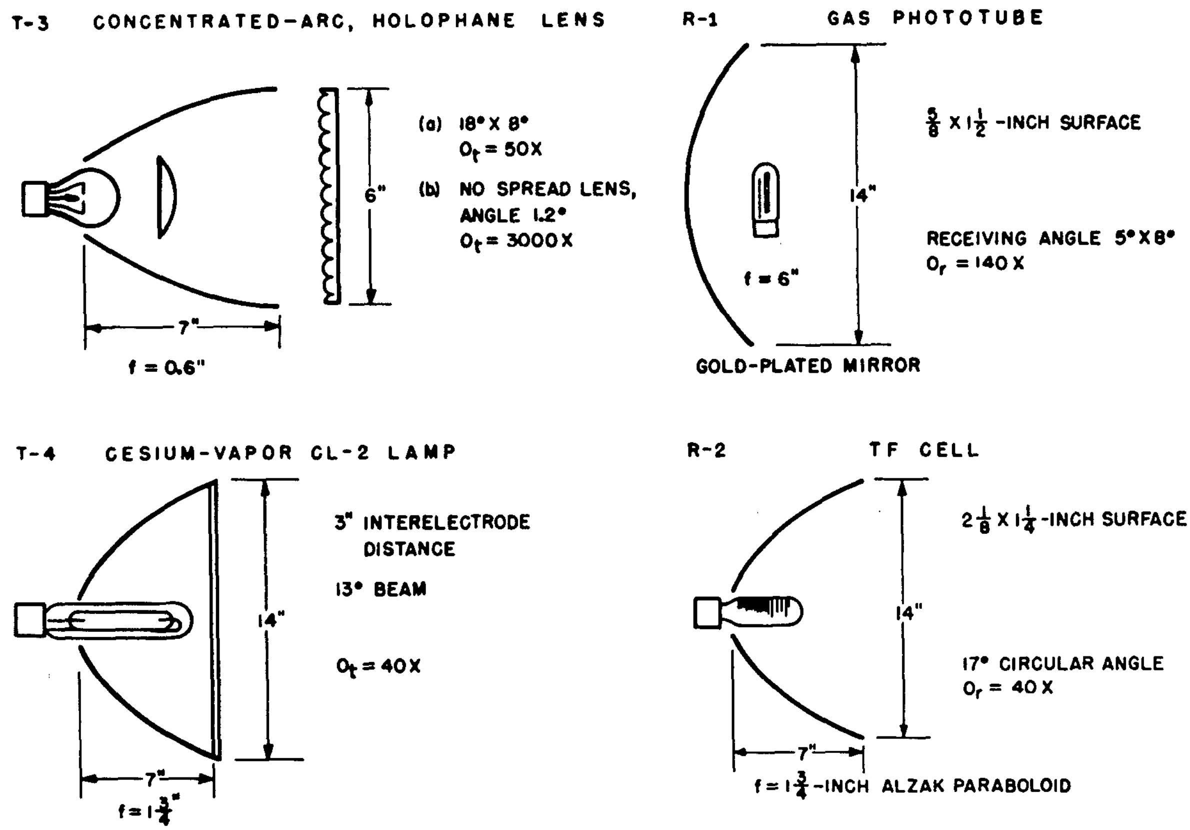


FIGURE 22. Optical systems, type E development.

peak-intensity width of 13 degrees. The optics factor is about 40×; it should be about three times this if the system were as efficient as the concentrated arc

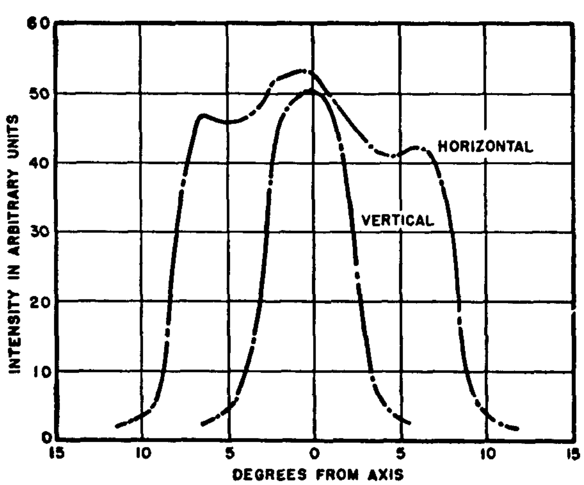


FIGURE 23. Intensity distribution from concentrated arc in projector arrangement T-3a of Figure 22.

systems just described. Much light is scattered at high angles: about 50 per cent of the total flux from the source falls inside a 50-degree circle, about 33 per cent inside a 30-degree circle, and about 22 per cent inside a 20-degree circle. Attempts have been made to devise more efficient systems for use with this arc, but they all lead to greater weight, size, and complexity.

The light in the central 20 degrees of the beam comes from only about 1½ or 2 inches of the 3-inch arc column length. A lamp with a shorter column, such as the 50-watt cesium lamp (2-inch column) produced for the aircraft systems (see "Source," Section 4.4.3) might be operated at lower power in this transmitter mirror and give almost the same maximum beam candlepower as the CL-2 lamp.

Phototube Receiver. In the first stage of development, the receiver consisted of a 14-inch diameter, 6-inch focal length, gold-plated, spun-metal, parabolic mirror with the cesium phototube at the focus (Figure 22, R-1). With this system, the CE-1-AB tubes mentioned above gave an hpr field of view of 5x8 degrees, the CE-15 tubes 4.5x29 degrees, the 2x4-inch tubes about 10x20 degrees, and the 6PEA multipliers a circular field 5 degrees across. The angles may vary by 20 per cent from one tube to

the next, as a result of variations in the sensitivity pattern, irregularities in the glass ends, slight differences in mounting, etc.

Only the large tubes, which had poor infrared sensitivity, gave fields approximating the 15- to 40-degree (presumably circular) width desired. The CE–1–AB system gave the best infrared response and was used in the tests in the first stage of development. A directivity pattern is shown in Figure 14, curve D.

TF Cell Receiver. Since a TF cell is sensitive to light impinging on both sides, it may be mounted for optical efficiency parallel to the axis at the focus of a fairly deep parabola so that both sides are illuminated, as shown in Figure 22, R-2 and already described. Typical directivity patterns for various cells and mirrors are shown in Figure 14; hpr angles again may vary by 20 per cent from one cell to the next. The best response throughout the central 20 degrees is given by the large 1¼x2⅛-inch type B TF cells mounted axially, in the same 14-inch mirror used for the cesium lamp transmitter.

Filters. The least dense filters used in tests in the concentrated arc stage of development were Polaroid XR3X41. They probably were more dense than necessary to give the 400-yard NVR desired, with the 18x8-degree, 5,000-hcp beam. The percentage response to the concentrated arc modulated at 1,500 cycles through this filter was 6 per cent for a CE–1–AB phototube and 16 per cent for a TF cell, compared with the response to the unfiltered light from the arc. These percentages are lower than the ehT values because they include the effect of decreasing modulation ratio for the arc at the longer wavelengths. It is estimated that these percentages might be three times as great for light transmitted by a filter chosen to give the maximum permitted visual range.

The filters used in the final laboratory model of type E, using the cesium lamp with a 4,000-hcp transmitter beam, were of the Polaroid XR3X with ehT values from 30 to 60 per cent. Measurements made by Contract OEMsr-990 indicate that Polaroid PVA filters and also recent OSU filters on white glass, with ehT values for the cesium lamp near 50 per cent, give NVR values for type E near the permitted maximum of 400 yards. Measurements made at the Naval Research Laboratory [NRL] indicate that the acceptable ehT values may be allowed to go as high as 80 per cent.

Assembled Equipment

Two stages of development have been distinguished. A typical assembly at the first stage of development, during the spring of 1944, included the following components: concentrated-arc source with large mirror-spread lens system, transmitter in open racks, carbon microphones and peak clipper, duplex operation, phototube detectors at focus of shallow mirror, tubes exposed to moisture, d-c receiver operation from batteries, dense filters, and transmitter and receiver heads on separate gimbals.

The summer of 1944 brought a transitional stage. A typical assembly then included more compact concentrated-arc transmitter optics, transmitters in drip-proof cases, dynamic microphones, better high-pass filters, phototubes in desiccated cases, TF cell receivers, a-c receiver operation, heads on a single set of gimbals, infrared telescopes for guiding.

By the fall of 1944 the cesium lamps had become available and the second stage of development, the final laboratory model of type E, was completed. The components of the assembly are given earlier in this section.

Interrelations of Components. Table 3 lists what are believed to be representative values of the total performance level of the two kinds of detectors with the two different sources and with various filters. The values may vary by several db from one lamp or one cell of the same kind to another. The signal level is given in decibels above the voice communication threshold (which is different for each cell-source combination). The measurements were taken with the bare cells in the uniform beam at an effective distance of 105 yards from the bare sources, which were fully modulated at 1,500 cycles per second. The circuits were the type E voice circuits. The measurements on the phototube have been increased 4 db [corresponding to the square root of the ratios of the areas of the cells, see Chapter 3] to compensate for its small size. From the observed signal level and distance, if the optics factors are known, the maximum bare-source, bare-cell range for threshold voice communication can be computed, and also the range for a complete system using such sources and cells.

In the first column of Table 3, the difference between the first and third (or second and fourth) lines gives essentially the modulation ratio of the concentrated arc, as the two lamps have about the

same holocandlepower and the cesium lamp has a modulation ratio of unity. For each line of the table, the difference between the first column and column (X) gives approximately the usable filter holotransmission for the different sources when mounted in the chosen transmitter systems.

TABLE 3. Total response of several combinations of sources, filters, and detectors (100-watt source fully modulated at 1,500 cycles). Figures show decibels above threshold voice signal; bare sources and bare cells at 105 yards.

Source	Detector	1 No filter (db)	2 Wratten 87 (db)	3 (X)*	4 XR3X-41 (db)	5 XR7X-25 (db)
1. Concentrated arc	TF cell†	29	24	(21)	13	12
2. Concentrated arc	Phototube‡	35	26	(23)	10	4
3. Cesium lamp	TF cell†	47	45	(44)	38	34
4. Cesium lamp	Phototube‡	54	52	(51)	44	38

* Estimated signal level with filters giving NVR of just 400 yards with transmitter systems T-3a and T-4 (Figure 22).

† 1¼x2⅛-inch grid, S/N = 57 db on U of M test set (Chapter 3).

‡ CE-1-AB (gas filled), ⅝x1½-inch surface; values corrected to larger size.

The values in column 3 are the most important for they indicate the comparative excellence of different source-cell combinations with optimum filters for sources or transmitters having the same holocandlepower. The cesium lamp-phototube combination is seen to be the best, but the cesium lamp-TF cell combination was chosen for the reasons indicated above under "Photodetectors." The total performance level of this combination is seen to be better by a factor of about 10 than the concentrated arc combinations, and thus corresponds to a factor of about three in vacuum voice range.

Operational Tests

Concentrated Arc System. Thirty-four night field operations were recorded during the development of type E. The first 22 of these were tests of the concentrated arc system, carried out in the period August 1943 to August 1944, the first 16 being over land and the remaining 6 over Lake Michigan. In all of these concentrated arc tests, one transmitter or transceiver was placed on the roof of Northwestern University Technological Institute, which is in Evanston on the shore of the lake, and the receiver or transceiver was located, for the tests over land, either in Grosse Pointe Lighthouse, 0.5 mile away, or at various beaches in Chicago and Evanston, up to 6 sea miles away. In the tests over water, transceivers were placed on the Navy lighter YF-538 which was made available for these operations by the Ninth Naval District. The customary procedure on the lake tests was for the ship to set out from the Naval Armory in Chicago, 12 miles away from the Institute, and sail toward the Institute until good voice contact was established with the shore unit. The course of the ship was then reversed and as it returned to the Armory, voice and code maximum ranges were determined on each leg of the trip.

The first reasonably successful communication was obtained over land in September 1943 between a 100-watt concentrated arc, mounted in an 18-inch parabolic reflector without filter, and a vacuum phototube receiver in a 14-inch reflector, connected to an amplifier having 70 db gain. The hpi angle was about 3 degrees and the range limit was found to be 4.1 miles for voice communication. Later, using the same source and a gas-filled phototube in a 14-inch reflector giving hpr angles of 5x8 degrees, good voice communication was obtained at 4 miles, and contact was established as far away as 6.8 miles, in a misty atmosphere.

Ship-to-shore tests in December 1943 with similar equipment gave 4.3 sea miles voice range, with 5-degree hpi angle and 5x8-degree hpr angles as above, with transmission about 0.6 per mile. This corresponds to a 20 sea mile vacuum voice range. With transmission 0.4 per mile, and 3.5-degree hpi angles, the ranges were 4.6 miles for voice (30 miles vacuum) and 8.9 miles for code, although the communication was carried on through ice on the pilot house windows.

In a ship-to-shore test on April 18, 1944, with the favorable transmission of 0.7 per mile, with 100-watt concentrated arcs in spread-lens systems and with the above receiver, the voice range was about 6.5 sea miles, and code was received until the line of sight was interrupted by the Navy pier at 10.6 sea miles. In this test, both 6x10-degree and 4x12-degree hpi angles were used, with XR7X filter. The 5x8-degree receivers were again used.

With the same equipment (except the filter, which was replaced by an XR3X type) in another test on May 15, under terrible weather conditions

with threatening rain and a transmission of about 0.1 per mile, the range was 2.2 miles for voice and 3.6 miles for code transmission. When the April and May ranges are reduced to vacuum conditions, however, the ranges for voice communication both came out at about 15 miles. This value is less than that of the December 1943 tests because of the use of filters and the widening of the beam in the later tests. During the May 15 test, high humidity progressively reduced the performance of the phototube receivers because of increased surface leakage. This experience was a major factor in stimulating consideration and use of TF cells instead of phototubes.

Two further concentrated arc ship-to-shore tests were made in August, 1944, using the new 18-degree hpr width TF cell receivers (which were in essentially their final laboratory-model form) and the final 8x19-degree hpi width concentrated arc spread-lens transmitters (Figure 22, T–3a). The ranges for voice were about 2.2 sea miles and the ranges for code 3.0 to 5.6 miles, with 0.5 to 0.8 transmission per mile. The range for voice communication in vacuum is thus about 8 sea miles, and the ACW range 3.5 sea miles. The filters used were XR3X on one test, XR7X on the other. The further loss in vacuum voice range is the result of the further increase made in the beam angles in an attempt to meet the original request for 15- to 40-degree angles.

Cesium Vapor Lamp System. In the August 31 test, the last of those just mentioned, one of the recently received cesium lamps was operated as a source for the first time. Fortunately, these lamps and the concentrated arcs were similar enough in electrical characteristics to be operable from the transmitter panels then being used for the latter. These same control panels with only slight modifications were therefore used throughout the remainder of the cesium lamp type E laboratory development.

The cesium lamp was placed for this test in an improvised optical system with 40-degree hpi angle, a system which later proved to have been very inefficient. Nevertheless, the lamp immediately showed its superiority over the concentrated arc, a result which had been expected from preliminary laboratory observations (see above, "Cesium Vapor Lamp" and "Interrelations of Components"). This cesium lamp system gave voice and code ranges of 3.8 and 5.0 sea miles, respectively, on this test, in 0.5 transmission per mile weather, at the same time that the final model of the concentrated arc system was giving 2.2 and 3.0 mile ranges. The vacuum voice ranges are 12 sea miles for the 40-degree hpi width cesium lamp system compared to 8 sea miles for the 8x18-degree concentrated arc system. Since a sufficient area of a suitable filter could not be obtained for this test of the cesium lamp, a thick cover glass was used as a substitute.

Immediately following this test suitable cesium lamp optical systems were built up and the transmitters were modified to give better starting and more reliable operation of the vapor lamps. The system was thus put into essentially its final form, as already described under "Laboratory Model," with 13-degree hpi and 18-degree hpr (TF cell) widths. No further changes were made in these final models except for some alterations in the filters used and some small changes in the preamplifier circuit constants.

The remaining 12 field tests, using this final system, were carried out in October and November 1944. The first three of these operations were ship-to-shore tests between the Institute roof and the YF–538 on the nights of October 4, 5, and 6. All the results of these tests were essentially the same, the vacuum voice range being about 17 sea miles, the ACW range 5 sea miles. Variations in transmission from 0.4 to 0.7 per mile on the three nights produced variations in actual voice range from 3.4 to 5.3 sea miles and in code range from 4.0 to 7.0 sea miles. The filters used were of XR3X41 Polaroid cellophane type with an ehT of 0.30 for the cesium lamp.

During the October 6 test, a representative from BuShips and members of Section 16.4 were present. A direct and careful comparison was made between the performance of the cesium lamp system and that of the final 8x18-degree concentrated-arc system. The latter gave 2.9 and 3.0 sea miles voice and code ranges (8 miles vacuum voice range again) at transmission 0.7 per mile, as compared with 5.3 and 7.0 sea miles for the cesium lamp system (17 miles vacuum voice range).

On this occasion measurements were also made, at a fixed range of 2 miles, on the maximum angle through which a transmitter or a receiver at one station could be swung and still maintain intelligible communication while the transceiver at the

other station remained fixed in direction. The concentrated arc transmitters could be swung over a total angle of about 18 degrees, as expected from the width of the spread lens beam in the horizontal plane; a TF cell receiving from this arc system could be swung over about 29 degrees. The cesium lamp transmitter had a total beam width, measured in this way and at this range, of 48 degrees and the TF cell receiver in this case had an angling view of about 40 degrees because of the stronger signal. Variations in individual judgment produce variations of several degrees in these widths, just as they produce variations of a mile or more in range determinations; however, with experience, such observations become more consistent. These measurements of beam widths at 2 miles agree qualitatively with laboratory measurements (see Figures 13, 14, and 17), but no quantitative comparison can be made as the laboratory work was usually not carried to angles as large as these, where the intensity (or response) has fallen some 30 db from the peak.

Cape Henlopen Tests. Following this October 6 demonstration of the superiority of the cesium lamp system, this final laboratory model type E equipment was taken to the BuShips test station at Cape Henlopen, where 9 further field tests were made in cooperation with BuShips on October 18 and 19 and on November 14 to 28, 1945.[16,17] A vacuum voice range of 30 sea miles, ACW range 6.5 sea miles, represents all of the results with fair accuracy. The improvement from the earlier October results may be due partly to a change of filters to Polaroid Cycle-Weld-bonded XR3X-55 nylon-base filters with ehT values of 0.50 and partly to small improvements in receiver circuits. Part of the difference in the early and late October ranges may be fictitious, since the earlier values were low because of overestimates of atmospheric transmission by the visual method used for the Lake Michigan tests. The Cape Henlopen vacuum ranges should be fairly reliable, as instrumental determinations of T were made during these tests by several different methods.[16,17] The actual voice and code ranges in the Cape Henlopen tests varied from 3.5 and 4.6 sea miles on November 15, when the transmission was 0.30 per sea mile, to values limited only by the horizon at 7.5 miles on November 18, with transmission 0.65 per sea mile; code ranges were limited only by the horizon on every test except that of November 15.

All the Cape Henlopen operations were ship-to-shore tests between the BuShips test station and the USS *Marnell* except that of November 18, which was a ship-to-ship test between the *Marnell* and the minesweeper YMS 462. The equipment was officially demonstrated on this occasion to representatives of the following branches of the Armed Services: COMINCH, SONRD, BuShips, NRL, BuAero, SSL, Signal Corps, AAF, and the WDLO with NDRC, as well as the British Admiralty Delegation. On this demonstration, the effect of lights and gunfire on the equipment was observed also.

The following paragraphs give a summary of the performance characteristics of the equipment as determined from the Cape Henlopen Tests.

Code Transmission. In eight out of nine operations in November the range for code transmission was limited only by the horizon (about 14,000 yards). On November 15, the atmosphere was hazy and the transmission values varied from 0.25 to 0.30. The limiting code range was 4.6 sea miles, corresponding to a vacuum code range of $R_r = 75$ sea miles. Only on this occasion was it possible to test code transmission speeds at distances beyond the limiting range of voice communication. The following quotation is taken from the report of this test issued by BuShips:[17] "Two messages were transmitted using code at over 20 words per minute, one of the messages being composed of arbitrary letter groups. The reception of both messages was nearly 100 per cent, with the errors due to the operators rather than to the lack of ability of the equipment to transmit at these speeds. In the opinion of the operators, at this signal level (7,100 yards, 0.25 transmission) the equipment can be keyed as rapidly as desired." The signals at 1,500 cycles came in very distinctly without the usual static background experienced in radio coding.

Ship-to-Ship Tests. The values of angular spread are sufficient for manual alignment to insure uninterrupted ship-to-ship voice communication during rapid maneuvering of ships, and when ships are experiencing heavy rolls. This was proved by the ship-to-ship tests carried out on November 18.

One projector was mounted on the USS *Marnell*, the other on the minesweeper YMS 462. Transmission was 0.64 per sea mile. The sea was rough and both ships rolled and pitched considerably. At 13,400 yards, when voice communication was still 100 per cent, both ships started making S turn, the *Marnell* (ahead) making 10 knots, the YMS (behind) 5 knots. A hard right and then hard left rudder swung the ships some 70 degrees off the base course on either side. Communication was continuous until the beams were interrupted by the ships dipping behind the horizon (7.2 miles) in the troughs of waves.

Official Demonstration. On the night of November 16, a demonstration was given which was attended by 19 representatives from the Army, Navy, and NDRC. Ship-to-shore communication was carried out between the USS *Marnell* and the Bureau of Ships test station. Voice reception was excellent up to 4.5 miles; at this range code trans-

mission was begun and carried out to the horizon limit at about 8.0 miles.

At 1.7 miles and at 2.65 miles the *Marnell* was anchored in position. At each position, six 40-mm guns fired tracers from Fort Miles in the direction of the ship and two star shells were fired from the *Marnell.* Prior to each firing several 60-inch Army searchlight beams were swept across the bay between shore and ship.

Searchlights. A whining and growling sound is produced in the receiver by light from searchlights. This probably is due to the sputtering of the carbon arc. As the beam is swung toward the receiver, the noise rapidly increases and blanks all other reception. The receiver is completely deadened when directly illuminated by the searchlight beam.

Gunfire. On the ship gunfire and shell bursts merely produced clicks in the receiver. At the shore receiver each flash from the 40-mm and 90-mm guns momentarily "blocked" the receiver. The effect of searchlights and gunfire could probably be greatly reduced by the use of an infrared filter over the receiver similar to that over the transmitter, with almost no loss in signal intensity. Three out of four listeners reported sentence intelligibility as still "very good."

Star Shells. At the test station, the star shells were in the field of view of the receiver and produced a low frequency rumble which cross-modulated with voice signals from the ship and ruined intelligibility.

Other Lights. An X-2A (infrared) beacon on shore caused a hum which interfered very little with reception at the shore station. Blinker communication lights on ships off shore did not interfere.

Conclusions. The following is an evaluation of the performance of type E equipment by the Bureau of Ships personnel:[17]

a. The range of the type E equipment is greater than 5 nautical miles for average weather conditions (based on 0.6 transmission for average conditions in the Pacific area).

b. Since the rolling and pitching of the two ships on the night of 18 November is considered equivalent to that which might be experienced by a destroyer in a fairly heavy sea, the beam angles are sufficiently large to maintain communication under most weather conditions when the equipment is installed on larger vessels.

Present Status

Following the successful tests at Cape Henlopen, the Navy undertook a procurement program with Belmont Radio Corporation and with Cover-Dual Sign Systems, Inc., both of Chicago, for quantity production of the type E equipment. Those working under Contract OEMsr-990 were authorized by OSRD to furnish consultant and advisory service for the manufacturing program.

At this writing, one prototype model from each manufacturer (Figures 15 and 16) has been tested by those working under Contract OEMsr-990 both in the laboratory and in a field operation. These models have been described in the summary above under "Production Models." Their general performance characteristics are essentially the same as those of the final laboratory models, except that they are built to Navy specifications and must pass the usual vibration, shock, temperature, corrosion, and weathering tests. Manufacture is continuing.

The laboratory equipment and the completed laboratory systems assembled under Contract OEMsr-990 have been transferred from OSRD to the Navy for continuation of the work of this contract at Northwestern University under Navy Contract NObs-28373.

Recommendations

Much work has been done on maximizing the performance of all the components of the type E system up to the limits practical for field operation. It is believed that the night ranges of this system are within about 1 mile of the maximum ACW ranges theoretically obtainable in the NIR with 100-watt sources of any kind, beam widths of about 15 degrees, and any existing detector cells.

It is not certain whether the bandwidths used in the transmitter and receiver circuits in either the laboratory or production models of type E really give optimum intelligibility and total performance for the system. It is thought that a few db may be gained by improvements at this point. Further improvement might be made by redesign of the transmitter optical system for greater efficiency of light output in the central 20 degrees and less radiation at wide angles. This would increase the central ranges and decrease the widths of the patterns shown in Figure 16; whether this is desired by the Navy is not known.

Some consideration might be given to adapting the type E system to daylight use (without loss of its night range) as mentioned under "Evaluation" above.

The xenon source (Section 4.5.3) should be studied as an alternative to the cesium lamp source.

A comparison should be made of the weight, power, range, and stability of mechanically modulated systems and electrically modulated systems for shipboard use.

The possible amalgamation of type E with an identification system such as type D is discussed in Section 5.2.

Probably no wide-beam, audio-amplitude-modulated, near-infrared system will long remain secure

against detection and possible interception of messages during military use in close contact with the enemy. A security device which can be incorporated in the present general design of type E would be a speech-scrambling system. Frequency modulation using a fairly low-frequency carrier wave (say about 20,000 cycles) has also been considered and would be possible, though perhaps inefficient, with the cesium vapor source; this would probably require the replacement of the TF cells in the receiver by phototubes.

Further improvement in security can be obtained only by going to narrow-angle systems, and/or to different wavelength regions such as the intermediate infrared (Section 4.8) or perhaps the ultraviolet. Use of narrow angles of course introduces the complications and limitations of associated tracking devices.

Conversion of type E to a narrow-angle system was considered by those working under Contract OEMsr-990. Simple replacement of the lamp and cell by a ¾-inch long cesium lamp and a ¼x¼-inch TF cell, both of which have been produced experimentally (Chapters 1 and 3) would give a 4- to 6-degree system with no other changes. Use of the final concentrated-arc transmitter optical system (6 inches in diameter) without spread lens (T-3b in Figure 22), and a ¼x¼-inch TF cell with a 6-inch diameter 4-inch focal length mirror, would give a compact system. With angles of 1 to 3 degrees this could be operated directly from the present type E control panel; the range should be about the same as for present type E.

4.4.3 Aircraft Systems; Plane-to-Ground Communication System (P–G)

Course of Development of Aircraft Systems

Following the successful completion of the cesium lamp type E system for ship-to-ship communication, Northwestern University Contract OEMsr-990 was assigned in March 1945 to the problem of adapting the same principles to the development of two similar voice communication systems for use in Army aircraft.[24]

The first system was initiated under Project Control AC-226.03, requested by the Army Air Forces. It was intended to provide voice communication at night between a hand-held unit on the ground and a hand-guided unit pointing out of the window or hatch door of a plane flying at between 500 and 1,000 feet altitude at about 125 miles per hour. The system was to be for use in situations involving the maintenance of communications and transport of supplies by air at night to guerrillas, paratroops, or other isolated ground troops. The ACW range was to be 3 miles.

Tests conducted at Wright Field indicated that minimum transmitting and receiving angles should be about 8 degrees ±2 degrees and 10 degrees respectively, for the ground unit and about 15 degrees ±5 degrees and 10 degrees, respectively, for the plane unit. These angles are necessary for making contact and maintaining continuous communication between hand-held units using auxiliary infrared electron telescopes for visual sighting.

A requirement was that the complete ground unit weigh less than 40 pounds, so that it could be carried to earth on the person of a paratrooper and that it have a self-contained power supply. This made it impossible to have the plane and ground units nearly alike, as had been originally desired, and still achieve the specified range and angles. Mechanical modulation was indicated for the ground unit, as this requires only very lightweight equipment, although the efficiency is low. It was decided that, by way of compensation, the plane unit (P-G system) should have a larger receiver mirror and an electrically modulated source operating from the aircraft power supply and that the weight of this unit (exclusive of cables) should be allowed to go as high as 60 pounds.

The development of the ground unit was allocated by Section 16.4 NDRC to University of California Contract OEMsr-1073, as this unit was already engaged on a similar problem. The completed ground unit, type W, has been described in Section 4.3.2. The data on range tests between the completed plane and ground units are given below.

The second aircraft system was designed under Contract OEMsr-990 as Army Air Forces Project Control AC-226.04. It was to provide voice communication between the adjacent planes of a bomber (B-29) formation under conditions requiring radio and radar silence. In two important respects this plane-to-plane (P-P) problem was a greater departure from the type E development than was the plane-to-ground (P-G) problem. The system was to be an all-around one, communicating

over angles of approximately 120 degrees horizontally by 60 degrees vertically at the front and also at the rear of a bomber. Also, it was to operate in daylight with the receiver illuminated by the equivalent of an average overcast north sky, the range to be at least ½ mile day or night. The weight of the whole system (exclusive of cable) on one plane was to be less than 120 pounds.

Electrically modulated sources were evidently required. It was decided, after inspection of a bomber of the B-29 type for which the equipment was to be designed, that the physical layout of the ship would require two transceiver units in the nose and one compact one in the tail in order to give the desired communication angles.

In constructing the equipments for these two projects, components were selected to meet Air Force specifications as far as possible, since the Army wished to put them into manufacture with the least possible revision and delay if they worked satisfactorily. This procedure makes it possible to predict accurately the weight, size, and mechanical and electrical performance of possible manufactured units. It also minimizes any adverse effects of low pressure, moisture, or cold which might be encountered in actual flight tests on the laboratory models.

When the end of World War II brought termination of the contract, neither of the two systems had been completed in the form intended. The P-P system had been considered more important by the Army at first, and an electronic power supply unit and control panel for operating three sources from aircraft voltages were finished by July 1945. Several questions connected with receiver design and the best use of photodetector cells for daylight communication had not been settled, and the transceiver heads were therefore not finished when, as a result of the changing military situation, the Army began to emphasize the urgency of completion of the P-G system. The transceiver unit for this system was promptly finished. To save time it was operated immediately in laboratory range tests with the type W unit using the three-lamp control panel already constructed. This combination of units was then shipped to Wright Field for actual tests between a plane and the ground. The end of the war occurred before a separate control panel could be built for the plane-to-ground unit.

In what follows estimates will be given as far as possible of the performance of the equipment if it is finished as designed, based on the performance of the completed units.

Description and Performance

General Design. The general design of the P-G system is not unlike that of type E (Figure 11) if the small separate amplifier box in the receiver line is replaced by a starting transformer box in the source line.[24] One complete aircraft installation should consist of (1) a cesium lamp source, reflector and filter, (2) a starting transformer box, (3) a photodetector, reflector, and preamplifier, (4) a control panel containing transmitting and receiving circuits designed for connection to the plane's intercommunication system, and (5) a power supply, which may be incorporated in the control panel.

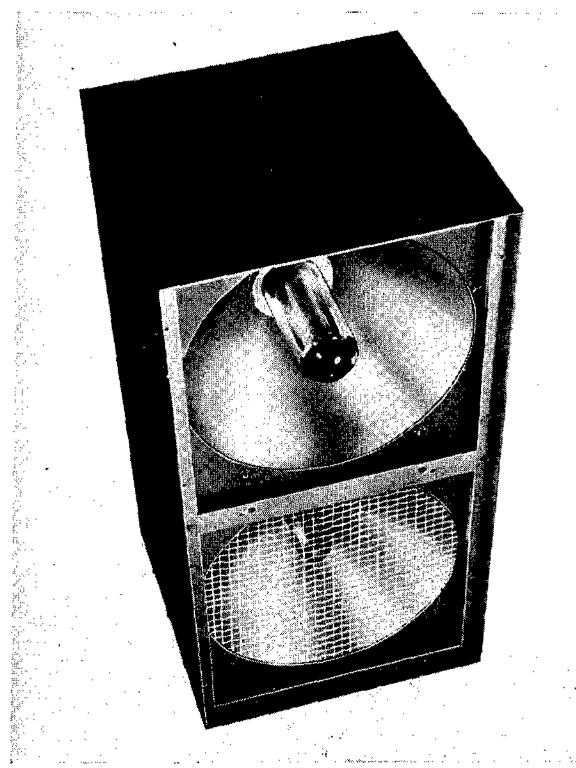


Figure 24. P-G transceiver head.

The transceiver head is shown in Figure 24. The infrared filter has been removed to show the source, which is an electrically modulated 50-watt cesium vapor lamp mounted axially at the focus of a 7¼-inch diameter, ⅞-inch focal length, Alzak aluminum parabolic reflector. The hpi width of the

emergent beam is 16 degrees and the transmitter optics factor is 18×.

The photodetector is a type A ¾x¾-inch TF cell mounted axially at the focus of an identical reflector which is covered by the electrostatic screen seen in Figure 24. The hpr width is about 12 degrees and the receiver optics factor 40×. The cathode-follower preamplifier is mounted in the back of the transceiver head.

In an actual installation the head would presumably be placed in gimbals or supported so as to rotate freely; it would point out of the hatch door on the left side of a cargo plane. An infrared electron telescope would be attached to permit an operator to sight visually on the ground unit.

A short cable connects the head to the starting transformer box and longer cables, if desired, to the control panel. The control panel was to be designed, as the three-lamp control panel of the P–P system is, to operate from the carbon microphones and to feed the headsets of the plane's normal intercommunication system so that the pilot or copilot could carry on the conversation. The conversation would presumably be monitored by the man guiding the transceiver head who might also operate the control panel.

The dimensions and weights of the units (exclusive of cable) would be:

Unit	Dimensions	Weight
Transceiver head	8x8x16 inches	10 lb
Starting box	4x6x8 inches	10 lb
Control panel	Combine in single unit less than 8 x 15 x 20 inches (size of combined 3-lamp P–P unit)	20 lb (est.)
Power supply		17 lb (est.)
Total weight		57 lb

The power consumption of the whole equipment would be about 120 watts from the 28-volt d-c plane supply plus an estimated 130 watts from the 115-volt 400-cycle a-c supply.

Security. The filter used over the transmitter is the Polaroid XRN5PX–55 PVA sandwich type. The NVR is computed to be about 230 yards from the measurements of Contract OEMsr-990 and about half this if determined by NRL methods (see "Filters," Section 4.4.2); it probably can be taken as equal within experimental error to the value of 400 feet specified in Project Control AC–226.03. The vacuum range for detection of the transmitter by a type C_4 infrared electron telescope is expected to be about 35,000 yards, and the ACW range about 10,000 yards. Since the telescopes are used for guiding it is desirable that this range be large. It is about 30 per cent larger than the communication range between the P–G unit and the type W ground unit so that the ground unit should have little difficulty locating the plane source before it comes within voice communication range.

Range. The vacuum communication range between this P–G unit and a 40-watt type W unit was determined in laboratory tests. The receiver performances of the two units are comparable (see "Laboratory Tests"), but the sources differ greatly in their efficiency, and consequently communication can be transmitted *from* the P–G unit *to* type W over a considerably greater range than in the opposite direction. This difference may be summarized as follows:

Communication	Vacuum Range	ACW Range
From P–G to type W	19,000 yards	7,600 yards
From type W (with 10x10-degree beam) to P–G	5.500 yards	3.600 yards

Calculations from these data indicate that the later 100-watt model of type W could be adapted to meet the request of Project Control AC–226.03 for a range of 3 miles (5,200 yards) between these two systems, by adjusting the beam spread to about 7x7 degrees. Then the last line of the above table would become:

From new type W (with 7x7-degree beam) to P–G	9,600 yards	5,200 yards

If the P–G unit were used for communication to a similar unit in another plane, as has been suggested, the vacuum range in either direction would be about 23,000 yards and the ACW range about 8,200 yards.

For communication between the P–G unit and a shipboard type E unit, the vacuum range in either direction would be about 35,000 yards and the ACW range about 10,000 yards.

Evaluation. The P–G system, if completed as originally designed, promises to have approximately the size, weight, range, beam angles, and security originally specified for it. No recommendations for changes can be made other than those already set down for the similar type E system (see "Evaluation" and "Recommendations," Section 4.4.2).

TRANSMITTER

Source. The most efficient near infrared source available at the time the aircraft projects were begun was the 90-watt CL–2 cesium-vapor lamp which had been developed for the type E system. This lamp was too large to use in the space available for the aircraft transceivers. Further, it seemed improbable that electronic equipment could be built for fully modulating any lamp consuming more than 50 watts of d-c power without exceeding the weight requirements. Accordingly, a smaller 50-watt cesium vapor lamp was produced by Westinghouse Electric Corporation at the request of the Army Air Forces and Contract OEMsr–990. The lamp has a voltage drop of about 12 volts at the rated current of 4 amperes, and an intensity of about 75 hcp measured on an RCA 919 phototube.

Lamp Operation. The principles of operation of these lamps will be mentioned here, postponing to Section 4.4.4 the details of design of the three-lamp control panel as actually built. It was found that the lamps, once started, would operate successfully in series with a suitable ballast resistance directly from the aircraft 28-volt d-c supply. A small, commercial, current-regulating, iron-wire ballast resistor tube was used in the control panel to maintain the lamp current at its rated value of 4 amperes.

Lamp Starting. To save weight in the aircraft installation, a simpler starting circuit is used for these lamps than for the type E cesium sources. To break down the arc gap, 400 volts a-c is applied to the lamp through a ballast resistor which limits the current to 0.5 amperes. After the lamp has been sufficiently warmed by this discharge, the a-c is removed and the 28-volt d-c simultaneously applied, and the current slowly climbs to its normal operating value.

Lamp Modulation. The output from the power amplifier is capacity-coupled directly to the terminals of the lamp as in type E. To avoid excessive dissipation of the modulator power in the low ballast resistor used here, a 4-millihenry choke is placed in series with this resistor.

Full modulation of the lamp is obtained with an amplifier capable of supplying about 15 watts to a 1.6-ohm resistive load. The modulator, as constructed, employed negative feedback and gave 28 watts output at 1,000 cycles with 2 per cent third-harmonic distortion; the excess power is ample to compensate for line losses. Except for the negative feedback and a high-pass filter which sharply attenuates frequencies below 900 cycles, the circuit is conventional. It is used here, for the same reason as in the type E system, to enable the upper voice frequencies which are important for intelligibility to be modulated in the arc at a higher level. Volume compression was not used because it complicates the circuits, produces distortion, and would give a high background noise between sentences as a result of the high ambient noise level in airplanes.

Control Panel. As has been mentioned, no separate control panel was built for the plane-to-ground problem. The transceiver was operated, in tests, from one section of the three-lamp control panel which will be described in discussing the plane-to-plane system, Section 4.4.4.

RECEIVER

Preamplifier. The preamplifier is placed in the back of the transceiver head immediately adjacent to the cell. It consists of a single high-gain pentode stage followed by a cathode-follower to furnish an output signal of reasonable level and at the same time to give a low internal impedance. The TF cell load resistor is about 2 megohms; about 75 volts is applied across the cell and resistor.

Amplifier. The principles of the amplifier will be described here although the control panel actually built will be described in Section 4.4.4. The amplifier is simpler than that of type E, since it does not require the narrow pass band for code reception. A high-pass filter is again used to reduce the noise below 900 cycles. A cutoff at high frequencies is not used (except for the decrease produced by a capacitor across the plate resistor of one tube), because it is felt that it would reduce intelligibility more than it would reduce noise.

With the exception of the high-pass filter, the receiver-amplifier is a rather conventional high-gain audio amplifier employing negative feedback over the power output stage. Since at the limiting range of the equipment the input signal developed by the photocell is of the order of 2 microvolts, and the Army Air Forces requested that at least 200 milliwatts be available to operate a pair of 600-ohm headsets, an overall voltage gain of about 140 db was required. In the plane-to-plane system five

pairs of headsets were to be operated in parallel, so the amplifier was actually constructed to give a total available power output of 1 watt. The amplifier was designed using miniature tubes throughout, except for the power output tube.

Optical System

Directivity Patterns. The beam widths desired were very similar to those obtained with type E. The P–G optical system was therefore made a small replica of the type E optical system, but using the 50-watt cesium lamp and the ¾x¾-inch TF cell instead of the larger lamp and cell in type E. The reflector sizes and arrangement are indicated in Figure 25, T–5.

The shapes of the resulting directivity patterns are similar to those shown for type E in Figures 13 and 14, but with the widths and optics factors given above under "General Design." The vacuum range of the P–G unit transmitting to another P–G unit is less than half that of type E transmitting to type E, because of the smaller source intensity and receiver area and the larger transmitter beam width in the P–G system.

The range of the P–G unit for an infrared electron telescope was given above under "Security."

Filter. The filter recommended for use with this transmitter is the Polaroid XRN5PX–55. The NVR has not been measured directly but was computed from the type E NVR measurements (see "Filters," Section 4.4.2) with the results given above under "Security." This filter is nearly perfect for the cesium lamp (see Chapter 2). Therefore, if any decrease of NVR of the P–G system is desired, it should be produced not by increasing the filter density, but by decreasing the lamp input power; either procedure results in a corresponding decrease in vacuum communication range, but the latter is more efficient.

An OSU filter on white glass, with an ehT of 0.5 or 0.6, should also be acceptable.

Operational Tests

Laboratory Tests. First laboratory tests with the P–G transceiver and the three-lamp plane-to-plane control panel showed the need of improved filtering inserted in the d-c line control panel to eliminate ripple pickup during reception, as described in "Operational Tests," Section 4.4.4.

Subsequent laboratory range tests between the P–G unit and type W indicated vacuum range values as given above under "Range." A comparative study of the sensitivity of the P–G and type W receivers was made by finding the vacuum range to each with a bare 90-watt cesium lamp source operated from a type E transmitter. The ranges were, to type W, 5,600 yards; to P–G, 6,700 yards. The increased range of the P–G receiver is accounted for almost entirely by its larger reflector area, as the sensitivity of the TF-cell receiver circuits is evidently about the same for both systems.

Field Test. One test was made of actual communication between the P–G transceiver and a commercial model type E system over distances between 3 and 4 miles, on August 22, 1945, during the course of a ship-to-shore test of the latter on Lake Michigan. No attempt was made to determine maximum range. The quality of transmission from the P–G unit appeared superior to that from type E, the quality of reception on the two units about the same.

Revisions. In the latter test it was found that generator ripple noise leaked into the receiver through electrostatic coupling to the photocell. This was cured by placing an electrostatic screen over the receiver mirror as shown in Figure 24. Further ripple noise came in as a result of backscattered light from the transmitter; subsequent laboratory tests indicated that the addition of a second section of L–C filter in the input d-c power lead eliminated the trouble.

Test at Wright Field. The P–P control panel and power supply, a starting box, the P–G transceiver unit, the added d-c line filter just mentioned, and a type W ground unit (the third one built, which had a 40-watt lamp) were sent to the Special Projects Laboratory at Wright Field in September 1945 for operational tests between plane and ground.

At this writing, one such test has been conducted and an informal report has been received from that laboratory. The test was carried out on a clear night with a bright moon and some ground haze. In transmitting *from the plane* (16 degrees hpi width) to the ground unit (10 degrees hpr width), about 85 per cent intelligibility was maintained to a distance of about 6 miles, with the plane at an altitude of 5,500 feet. In transmitting from type W on a 12-degree beam *to the plane* unit (12-degree hpr width), intelligibility was reported at about 25 per cent at a distance of 1 mile with the plane at an

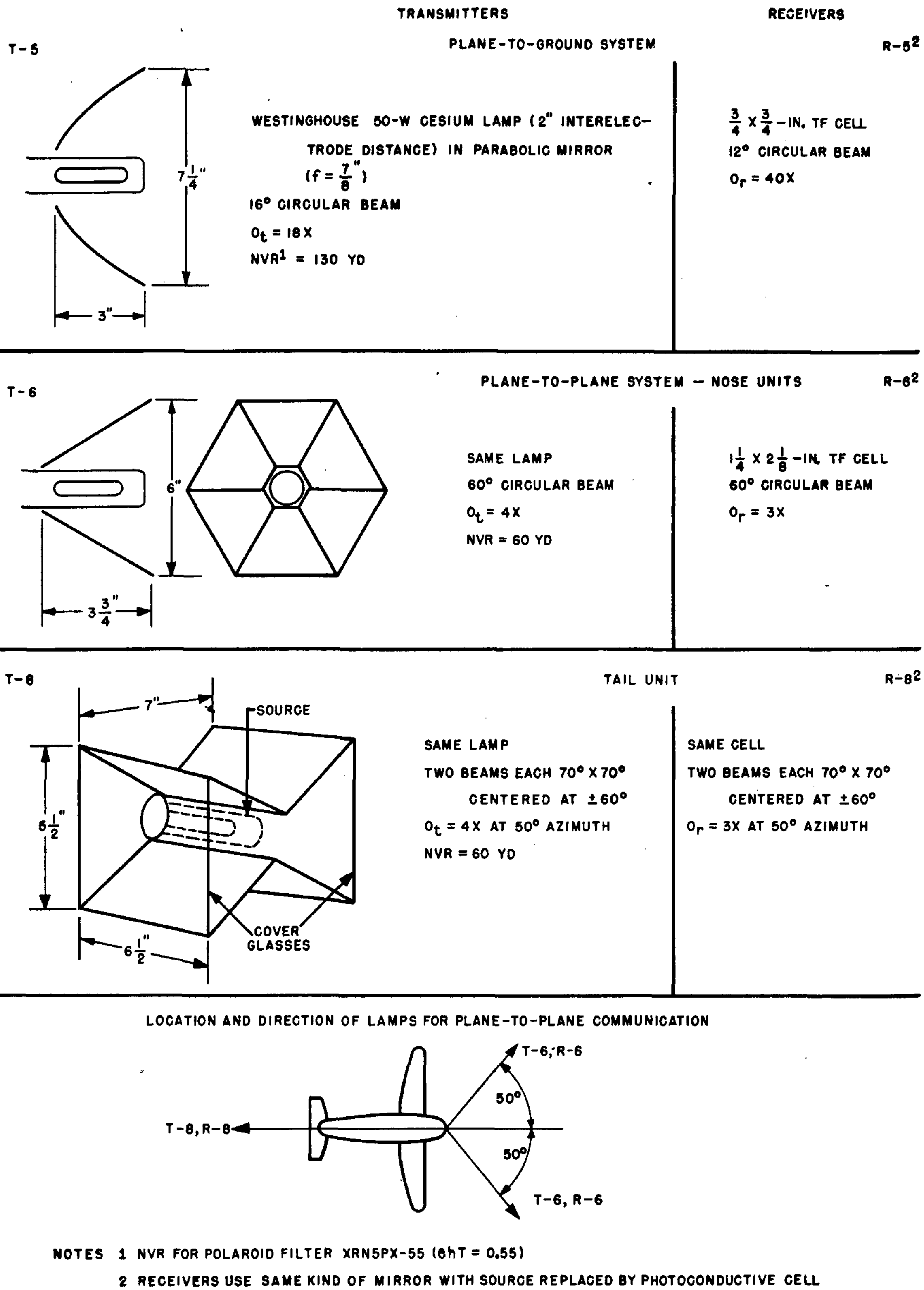


FIGURE 25. Aircraft optical systems.

altitude of about 1,000 feet. A visual signal lamp was used to maintain contact at the larger ranges.

The personnel of the Special Projects Laboratory was reported to be pleased with the general performance of the P–G unit but dissatisfied with that of the particular type W unit used, which employed a 40-watt source and wide beam. Various difficulties with the P–G unit were reported, such as the tediousness of lamp starting, which may have been due to undervoltage on the aircraft generator. There was high noise at the plane receiver, both ambient and from backscatter. The latter is probably due to placing the unit too far inside the hatch door. It should be located within a few inches of the airstream and well clear of the door frame. It was essential in avoiding backscatter in type E, for example, that no local objects be within about 50 degrees of the axis of communication at any time.

There was a great deal of trouble in maintaining contact between the units. This will undoubtedly disappear when the inferior charged-phosphor infrared image tubes (metascopes) are replaced by the recommended C_4 electron telescopes. The beam and receiver angles of the units are very close to those specified from the early tests at Wright Field (see "Course of Development of Aircraft Systems," above). If adequate telescopes are used there should be no more difficulty than those early tests indicated.

Most of these troubles will undoubtedly decrease as the operating personnel become more familiar with the units. Especially, it seems likely that the range *from* type W will come more into line with the laboratory estimates (see "Range," above) after the operators become expert in making and maintaining the very delicate grid adjustment in the laboratory model. Two of the improved 100-watt type W models have been sent to the Special Projects Laboratory for succeeding tests.

It is of interest that in this first test the difficulties anticipated with noise in the receiver from the hot motor exhaust did not materialize.

Present Status

The units listed above have been left at Wright Field for further tests. It is expected that Navy Contract NObs–28373, which is continuing the work of Contract OEMsr–990, will be consulted in connection with any further development of the aircraft units.

Recommendations

The P–G unit appears to meet the specifications for which it was designed. Whether the type W ground unit needs further improvement and whether changes are necessary in the P–G unit can be decided only after more extensive operational tests.

Probably mechanically modulated systems should also be built up and compared with the plane unit for aircraft use. They are less efficient and may be susceptible to vibration, but the modulator weight is negligible and the inefficiency may be counterbalanced by the use of very high-powered tungsten lamps with little increase in weight. A mechanically modulated system might be built to Air Force specifications with a weight of the order of 40 pounds. With a 1-kilowatt tungsten lamp source it might give ranges and angles comparable to those of this cesium lamp unit.

4.4.4 Aircraft Systems: Plane-to-Plane [P–P] Communication System

Description and Performance

The specifications and course of development of the plane-to-plane system have been discussed in Section 4.4.3. The P–P installation on a single bomber was to consist of (1) three fixed transceiver heads, each containing a source, photodetector, optical systems, and a receiver-preamplifier, (2) starting transformer boxes for the three sources, (3) a control panel containing the transmitting and receiving circuits, capable of modulating one source at a time and receiving from one or all of the receivers at one time, and connected with the plane's intercommunication system, and (4) a power supply which could be incorporated in the control panel.[24]

General Design. The location of and the direction of the axes of the three heads, two in the nose and one in the tail, is indicated in the sketch at the bottom of Figure 25. Sample heads were completed except for preamplifier circuit details connected with the choice of detector cell. The sources were the 50-watt cesium-vapor lamps (Chapter 1) and the photodetectors were to be either the large type B (2x1¼-inch) TF cells or PbS cells of the same size or larger, if they proved better for daylight communication. The optical units were con-

structed to give the greatest intensity and response in the general direction of the adjacent planes in a normal flight formation, that is, at about ±50 degrees azimuth, and zero degrees altitude, with respect to the flight axis.

This distribution is obtained at the nose of the ship by pointing the unit on each side at 50 degrees away from the line of flight. The radiation source and detector cell are each placed axially in a 6-inch diameter hexagonal cone, made of 6 plane mirrors as shown in the sketch under T–6 in Figure 25. The beam from such a system is, of course, very uniform, the hpi and hpr fields both being close to 60x60 degrees. The transmitter optics factor is about 4×; the receiver optics factor is less, about 3×, because of the geometry of the cell.

Of two tail transceiver models constructed, the best was a unit intended to be mounted high up in the vertical stabilizer of the ship. In this unit, transmitter and receiver each have two apertures, one on each side of the ship, about 6 inches square. Source and cell are each surrounded by five plane mirrors as shown under T–8 in Figure 25. The distribution of intensity and response is expected to be in two beams, each about 70 degrees by 70 degrees square, centered at ±60 degrees azimuth from the line of flight. The transmitter optics factor at ±50 degrees should be about 4× and the receiver 3×.

The directivity pattern of this unit has zero range directly to the rear of the plane as far as ±25 degrees away from the line of flight. The other tail unit which was built had its maximum range directly to the rear but was much poorer at ±50 degrees from the axis, in the direction of the adjacent airplanes.

The nose and tail transceiver units must each have a starting transformer box near by. A single control panel in the center of the ship contains the other transmitting and receiving apparatus for the three transceiver units (Figure 26).

The dimensions and weights of the units are:

Front transceiver heads (8 lb each)	8x8x14 in. each	16 lb
Recommended tail transceiver head	8x10x13 in. each	15 lb
Starting boxes (10 lb each)	4x6x8 in. each	30 lb
Control panel } may be combined	8x10x19 in. each	24 lb
Power supply } may be combined	5x8x19 in. each	17 lb
Total weight		102 lb

The expected power consumption of the whole equipment would be about 350 watts from the 28-volt d-c plane supply plus an estimated 130 watts from the 115-volt 400-cycle a-c supply.

Security. The filter used over each transmitter is the XRN5PX–55 PVA sandwich-type Polaroid filter; an equivalent OSU filter could be used. The NVR is about 110 yards for each transmitter unit as computed from the type E NVR measurements of Contract OEMsr–990 and about half this if determined by NRL methods. It would seem desirable to relax the specification of 40 yards NVR given in Project Control AC–226.04, if work on these systems is to be carried further. The filters are nearly perfect for the cesium lamp. Therefore any reduction below the present visual range will reduce the communication range, which already may be short of the desired minimum value.

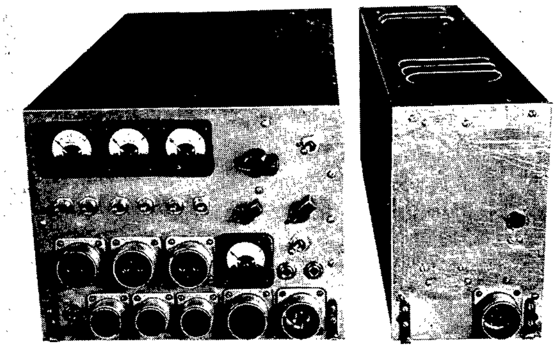


FIGURE 26. Three-lamp P-P control panel and power supply.

For a type C_3 or C_4 infrared electron telescope the estimated maximum vacuum range of detection for each of the transmitter units is about 16,000 yards and the ACW range 7,000 yards.

Estimated Range. Because of the unsolved problems connected with the best use of photodetector cells in daylight operations, only order-of-magnitude estimates of daylight range can be given. These estimates predicate the use of TF cells as photodetectors; present information on sensitivity and behavior with background light of PbS cells is too scanty even for such estimates.

The TF cell daylight range estimates are based on two sets of data: (1) night ranges computed for the P–P system from the lamp holocandlepower, cell sensitivity, and optics factors, the computations being based on experience with type E

TF-cell receiver circuits; and (2) preliminary laboratory measurements with TF cells of the loss in sensitivity (S/N ratio) produced by background illumination roughly equivalent to average overcast north sky light, the measurements being made with the receiver load resistor properly reduced to compensate for the reduced resistance of the cell under these conditions. In these measurements of background effects the cell was covered, as it should be in all daylight work, by a filter similar to that over the transmitter so as to reduce the background intensity as much as possible as compared with the signal.

The first set of data, the computed night ranges for the P–P system, gives the following result: maximum vacuum voice range, at azimuth ±50 degrees and altitude zero degrees, about 4,000 yards, ACW range about 2,800 yards, both values being subject to uncertainties perhaps of the order of 30 per cent. For night communication between two airplanes flying parallel in the same horizontal plane, the variation of range with azimuth is shown in Figure 27A (one quadrant). The variation with altitude, when the line between the airplane is at 50 degrees azimuth, is shown in Figure 27B (one quadrant).

In the second set of data, the sensitivity loss of TF cells, with daylight background but under optimum conditions, was measured at about 20 db. With such a loss, the vacuum range of the system would be reduced by a factor of about 3, giving an estimated daylight vacuum voice range of about 1,200 yards, ACW range of about 1,000 yards. These daylight range estimates are uncertain by perhaps a factor of 2 in either direction, and indeed the ranges might vary by this much or more from day to day, or from low to high altitude, or from one direction of flight to another. With present circuits, unless the optimum daylight load resistor is changed for use at night, the night ranges will be only slightly greater than these values. However, a proposed new circuit (see "Preamplifier" in this section) may make it possible to obtain both optimum day performance and optimum night performance with the same circuit without any changes.

The PbS cell is less sensitive to background light than the TF cell but also has a much lower sensitivity in the dark. However, its sensitivity increases at low temperature and it might be placed so as to be cooled by the airstream and protected from the heat of the transmitter to take advantage of this property. Whether it would be better or worse than the TF cell for average daylight conditions cannot be predicted at present. It might operate in direct sunlight where a TF cell would be completely deadened.

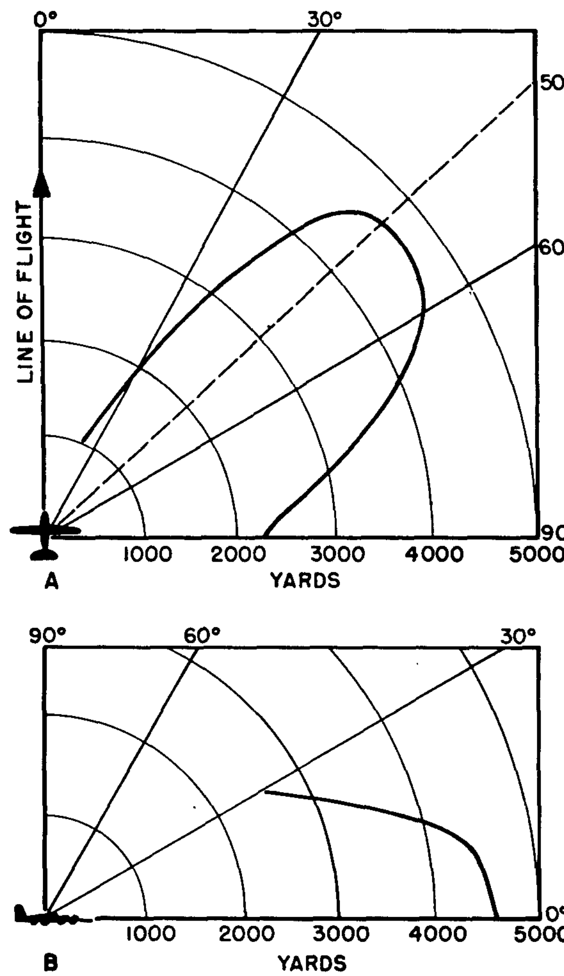


FIGURE 27. Area of two-way night communication, P-P system (planes flying parallel). With (A) vacuum night range as a function of azimuth and altitude 0°, and (B) vacuum night range as a function of the altitude angle and azimuth 50°.

The use of a streamlined shelf projecting out a few inches into the airstream to act as a sunshade over each of these receiver optical units might materially increase daylight communication range for TF cells and still have little effect on the angle of view of the receivers.

Evaluation. The system probably will not meet the specifications of an NVR of 40 yards, which, however, seems unnecessarily stringent. The ques-

tion of whether it will meet the requirement of ½-mile daylight range cannot be settled except by operational tests and further work on receiver circuit design and comparison of results with different types of detector cells. Whether, in the system as designed, the distribution of intensity and of response as functions of azimuth and altitude would prove satisfactory to the Air Forces is unknown.

There are too many transceiver units in this design and they are too far apart for efficient operation (the B-29 fuselage length is approximately 100 feet). A single unit on top of the tail or in a blister above the fuselage might give better angles of view and could be operated at considerably higher power for the same total weight.

The estimated short range is a direct consequence of the wide angle of view desired. If it proves too short to be of military value it can be increased, with this angle of view, only by using much higher powered sources. Mechanical modulation of tungsten sources of 1 kilowatt or over might give better range and require less weight, as mentioned under "Recommendations" in Section 4.4.3.

Transmitter

Lamp: Operation, Starting, Modulation. The lamps used and the principles of operation are the same as described for the P-G transmitter in Section 4.4.3.

Control Panel. The basic modulation circuit is described under "Lamp Modulation" in Section 4.4.3. To reduce weight, only a single high-pass wave filter was used. It was shifted by the send-receive switch from the modulator to the receiver as needed.

The three receiver preamplifier outputs are amplified through one stage and then mixed electronically before going to the high-pass filter. The selector switch provides that any one or all of these three channels can be in use at any one time. Each channel is completely independent of all of the others.

In *send* position, the output from the wave filter goes to the feedback section of the modulator power amplifier; in *receive* position, to a small two-stage power amplifier for operating from one to five sets of 600-ohm impedance headphones.

The high-voltage power supply was constructed on a separate chassis to avoid hum leakage from the 400-cycle power transformer to low-level amplifier components, but this precaution proved unnecessary.

Figure 26 shows the control panel and power supply. The three ammeters read the lamp current of each transmitting channel. The voltmeter reads the d-c arc voltage drop of the lamp which is being modulated, or if the lamp is not running it indicates this fact by reading d-c line volts. The switch in the upper right-hand corner is the send-receive switch. On the left of the send-receive switch is the channel-selector switch. It has four positions: send-receive on channels I, II, or III only, or, in the fourth position, receive on all three channels.

Receiver

Photodetector Cell. The cells considered under Contract OEMsr-990 were the type B TF cells used in type E, and a PbS cell of the same size, constructed under Contract OEMsr-235 for this problem.

Preamplifier. The basic preamplifier circuit is that described under "Preamplifier" in Section 4.4.3 for the P-G system. The difficulty with the TF cell in such a circuit is that its resistance may decrease by a factor of 50 in going from dark to daylight background. If a simple fixed load resistor is used in series with the cell as in the other aircraft system, maximum power output evidently cannot be obtained under both conditions. It is not feasible in aircraft applications to change the resistor to meet different background conditions. The best present solution is to use a resistor suitable for daylight operation; night range will then be slightly greater than day range but much less than the maximum night range obtainable with the optimum load resistor for night operation.

There was no time to try one solution to this problem which seems promising. This is the use of an audio reactor, with an inductance of 10 henries or more and a resistance of 500 ohms or less, in place of the load resistor. With such a choke feed, the cell voltage would remain constant day or night and no switching arrangements would be necessary to provide optimum operating conditions. The choke may also introduce some correction for the decrease in cell response at higher audio frequencies.

Even with optimum adjustment of resistance the sensitivity of the TF cell decreases with background light. Laboratory measurements made under the

equivalent of 1,000 footcandles illumination from an overcast north sky showed in one cell a loss in S/N ratio of the order of 20 db as compared to the ratio for the cell in the dark.

Circuits for the PbS cell would probably be basically the same as for the TF cell, but time was lacking for making detailed studies.

Amplifier. The principles of the amplifier for the P–G system have already been described under "Amplifier" in Section 4.4.3, and details have been mentioned above under "Control Panel."

Optical Systems

The first laboratory units of this equipment were to be designed to operate through existing windows in the B–29 bomber without any new construction of transparent blisters and were to be mounted in easily accessible places, such as the nose blister and tail gunner's compartment.

It appeared that the use of a single unit in the center of the nose would interfere with the operation of the plane, so it was decided to have two nose units, one on each side, as described above under "General Design." The size and arrangement of parts in these P–P nose units can be the same as in the P–G transceiver, except for the change in reflectors.

At first an attempt was made to design a tail transceiver unit for a space 8 inches deep, with both optical apertures fitting into a 3x11-inch opening, just over the tail window of the ship. This space was found to be too small for any optical systems giving the desired distribution. A unit was then built for use in the vertical stabilizer as described.

The rear side of the box housing the latter transceiver may reflect radiation from the airplane's own motors into the detector cell. On this account, this surface may perhaps need to be painted dead black as the TF cell is fairly sensitive to low-temperature radiation and the PbS cell extremely so (Chapter 3). The pulsed exhaust radiation may cause a serious noise problem in the receiver in spite of the filtering out of the low-frequency components. (However, see "Test at Wright Field," Section 4.4.3.) Whether the radiation from the exhausts of adjacent planes will also cause trouble is unknown, though it seems very likely with the PbS cell.

All three transceivers should have filters over both the transmitters and receivers for daylight use with TF cells. Each unit should be mounted with the transmitter above and the receiver below and with a streamlined shelf projecting out into the airstream between the transmitter and receiver as a sunshade. The units should not be placed inside existing windows in such a way that the transmitter beam can reflect back from the window into the receiver.

The estimated range curves shown in Figure 27 have been computed from laboratory measurements of the directivity patterns of the units actually built.

Operational Tests

Since the receiver cell and preamplifier questions had not yet been solved, at the time of termination of the experimental work of the contract caused by the end of the war, no operational tests with these transceivers were made. Rough range estimates have been given under "Estimated Range" above.

The operation of the control panel was checked in the P–G "Operational Tests" (Section 4.4.3). In the first of these tests it was found that 400-cycle harmonic ripple frequencies leaking back from the laboratory aircraft generator into the 28-volt d-c line were causing a great deal of noise in the receiver. This was cured by inserting a single-section L–C filter in the d-c power line and by changing to a double-section R–C filter in the d-c supply voltage for the photocell. The later outdoor field test showed the need of further filtering to avoid the noise from backscattered light. Laboratory tests indicated that a second section of L–C filter in the d-c line eliminated the trouble. The control panel then worked quite satisfactorily.

Present Status

The P–P control panel is at Wright Field for tests on the P–G system (see "Present Status," Section 4.4.3).

Recommendations

The communication ranges, security, and daytime ranges of the P–P system promise to be close to the desired values. Whether or not this particular system is of continuing military interest, an incentive for completing and testing it further should come from the large number of interesting associated problems on which it is important to get exact quantitative data in considering military applications

of the infrared for aircraft in general. Some of these problems are:

Proper number and location of transceiver units on aircraft for best communication.

Comparative weight, power, range, and stability of mechanically modulated versus electrically modulated systems.

Problems connected with day-and-night receiver operation (also important for ground infrared uses), such as optimum circuit design, measurement of actual daylight and sunlight effects, choice of cells, and filtering and shading of receivers against background light.

Improvements and changes in performance of receivers at high altitudes as a result of cold and low background light.

Effect of engine exhaust radiation on voice and other reception with different types of cells.

Associated with the consideration of mechanically modulated systems and PbS cells on aircraft is the possible use of the intermediate infrared, with its greater security against enemy detection (Section 4.8).

4.5 CARRIER-WAVE SYSTEMS

4.5.1 Types of Systems

Three different types of infrared communication systems have been devised in which audio amplitude-modulation may be superimposed on a higher frequency carrier-wave modulation of the radiation beam. In the type exemplified by the two systems to be discussed in Sections 4.5.2 and 4.5.3, a gas discharge source is electrically modulated at high frequencies. In another type, reported in Section 4.6, the state of polarization of the beam is modulated by use of the photoelastic effect in a block of glass strained by a standing wave. In a third type (the Scofoni system), not developed by NDRC, the beam is spread into an intensity-modulated diffraction pattern by a "grating" of standing supersonic waves in a liquid.

Such carrier-wave systems may make use of some advantages not possessed by audio-frequency systems. (1) By using receivers tuned to the radio frequency, communication may be carried on in many different carrier-frequency channels, just as in radio. (2) They can be made secure against reception by ordinary audio-frequency receivers simply by changing them over from amplitude-modulation to frequency-modulation, or by superimposing the r-f on a steady d-c current.

A German system using r-f FM with a cadmium-compound detector cell was apparently produced during World War II, but details are not available. The source may have been a gas discharge of the type described in Sections 4.5.2 and 4.5.3 or the infrared mercury lamp already mentioned in Section 4.4.1.

Signal Corps Optiphone

The Scofoni system mentioned above has been applied in the U. S. Army Signal Corps optiphone.[11] This is a very narrow-beam (¼ degree) system, with a narrow-angle receiver, obviously for land use only, with ACW voice ranges of the order of 5 miles at night and 3 miles in the daytime. It operates as follows. As the amplitude of the standing supersonic waves in the liquid is varied by the modulation, the effect of the diffraction grating formed by the waves changes, throwing more or less light out of the central beam into the first and second diffraction orders which lie within about 1 degree to the right and left. This transmitter is not secure against audio reception, but the narrow beams probably are secure enough anyway; only an audio receiver is used in the system. Since this system and the photoelastic shutter system use the same supersonic modulation principle in quite opposite ways, some further remarks will be made about this system under "Comparison with Optiphone" in Section 4.6.2.

4.5.2 V–M System

One electrically modulated gas discharge carrier-wave communication system was studied by the V–M Corporation, Benton Harbor, Michigan, under Contract OEMsr-1460.[25] On account of the very preliminary state of the equipment as demonstrated, the much more complete development of other communication systems, and the status of the war, the development of this equipment was discontinued after a few months.

The source was a gas discharge tube, filled with krypton and xenon, which operated at about 500 volts at a maximum continuous current of 50 milliamperes d-c and which could be modulated at frequencies up to 100 kilocycles. The portable, battery-operated receiver used a gas-filled cesium-

surface phototube and a superheterodyne circuit. The system was demonstrated to NDRC and representatives of the Armed Services on July 6, 1945, in a darkened basement over a range of 50 feet. It was found that the source tubes were overloaded by voice modulation so code was used.

Since a complete check of the transmitter operating voltages and of the optical characteristics of the transmitter and receiver could not be made during the short period of the contract and since the gas discharge source used was in a very incomplete state of development, the maximum operating range which might be achieved with the system is unknown.

4.5.3 Touvet System

A much more successful system was built under Contract OEMsr-1391 which was set up by request of BuShips under Project Control NS-243 to provide facilities for Captain Guy Touvet of the French Navy to construct and test a radio-frequency system of his own design for voice and code communication.[26] Captain Touvet is an officer of the Société d'Applications Scientifiques, affiliated with the Claude Neon interests, which built a similar apparatus in 1939 for the French Navy. As the inventions were not covered by United States patents, he refused to disclose any details of the system being constructed until it was sold to the U. S. Government in September 1945. The description here is accordingly based only on his own statements, on observation of the equipment during demonstrations (especially during the *type E reception* described below), and on papers which he turned over to BuShips at the time of the sale. The account here is necessarily fragmentary and may contain conflicting statements.

French Prototype Model

The prototype system was said to have been tested in Algiers with an observed range of 16 miles at night and about 2 miles in daylight. The 200-watt radiation source was a Pyrex tube filled with rare gas, made invisible by a cellophane filter which gave a beam 30 degrees wide when placed in a 60-centimeter diameter reflector. The modulating system required 2 kilowatts of power. Two types of detector tube were used: a resonant gas cell and a special design of tubular cell. The hpr receiver angle was 3 degrees.

Description and Performance of Present System

General Design. One transmitter and one receiver unit, of approximately the design given for the prototype model, were constructed under Contract OEMsr-1391. The transmitter consists of (1) a gas discharge source mounted in a large reflector, and (2) a control panel containing a power supply and voltage stabilizer, the r-f exciter and modulator, and an audio modulator, as well as code oscillators. The receiver consists of (3) an undisclosed kind of phototube mounted at the focus of a large lens, and (4) a control panel containing an r-f receiver with audio amplifier designed to feed a high-speed telegraph recorder, a loudspeaker, or earphones. The transmitter control panel is about 18x24 inches in cross section and 6 feet high, weighing perhaps 450 pounds. The receiver control panel is about 18x24 inches by 3 feet high weighing perhaps 150 pounds. One transmitter mirror used was 24 inches in diameter and 10 inches in focal length; the receiver lens was 13 inches in diameter and 18 inches in focal length. The hpi and hpr angles are about 25 degrees and 2 degrees respectively. The transmitter draws about 12 amperes from a 110-volt, 60-cycle supply, and is designed to modulate a much higher powered lamp than the 200-watt source actually used.

The carrier frequency is of the order of 120 kilocycles in the present system, and any one of six channels can be selected at the transmitter or receiver end. The carrier may be amplitude-modulated by voice or code; or frequency-shift coding may be used for greater security.

Security. Through the filters used, the visibility of the source is comparable to that of the type E cesium lamp source through XR3X41; this implies an NVR of near 100 yards. An NVR of 500 yards using Navy binoculars was claimed for the French prototype model.

Also, the apparent brightness of the present system viewed by an infrared electron telescope is similar to that of type E, suggesting an ACW image tube range near 9 miles. Modulation of the source produces no apparent flickering in an image tube.

All panels and the whole transmitter cabinet are fully shielded to prevent broadcasting of r-f electrical radiation.

The amplitude-modulation of the carrier wave

makes possible voice reception by a simple a-f receiver, such as that of type E, to about the same range as the system's own receiver.

Range. The ACW range seems to be about 6.5 sea miles, vacuum range about 30 miles, with an 80-watt source input power such as that used in the outdoor tests. If the transmitter will modulate a 500-watt source, and if such sources are available, the ACW range might increase to about 8.5 sea miles.

Evaluation. This system can perhaps best be compared to type E. The present model has perhaps three times the weight and bulk and consumes almost twice the power of the type E laboratory model. With the source power for which it was designed it might give perhaps 2 miles more range than the latter. It has a larger transmitter beam angle than type E but a receiver angle of only 2 or 3 degrees compared to the 18 degrees of type E. At present it has no more security than type E against reception of voice communication by other audio receivers. Such message security should be one of the main reasons for using an r-f system and was requested in Project Control NS–243.

The detector is rather sensitive to background light and trouble may be encountered from backscatter if a transmitter and receiver are used side by side.

The multichannel feature of the present system might be very useful in convoys. Also it can be easily adapted to a "lock-in" tracking system guided on a steady code tone from the transmitter which would not interfere with simultaneous voice communication on a separate channel.

TRANSMITTER

Source. The source is a long Pyrex tube about ½ inch in diameter shaped into two flat spirals on top of each other. They are 4 inches in diameter and 1 inch apart. The tube is filled with xenon and possibly small quantities of other gases at a low pressure (probably about 5 millimeters of mercury). The electrodes are oxide-coated tungsten spirals. The coiled discharge tube is enclosed in a flat box with a glass front. A mirror forms the back of the box, reflecting radiation back through the source to increase the candlepower.

Since apparently only one of the sources brought from France was still functioning during the final tests, it was conserved by being operated at about 40 per cent of its rated power of 200 watts. The voltage drop was reported to be 80 to 100 volts at r-f currents of 1 to 2 amperes. It is said that lamps of this kind can be built in sizes up to 1,000 watts.

One of the features claimed for this source is that its spiral shape gives it a self-inductance and a natural r-f oscillating frequency which can be used to advantage in producing the modulation.

The lamp has a pale bluish-white appearance when viewed without a filter. The radiation is said to consist of a many-line or banded spectrum, with no appreciable continuum, in the range from about 0.7 μ to perhaps as far as 3.0 μ. Over 70 per cent of the input energy is claimed to be radiated in this region, most of it concentrated between 0.78 μ and 1.0 μ in the present system. However, the type E comparisons given under "Type E Reception of Source" indicate that the holocandlepower of this source, when run at 80 watts, must be comparable to that of a 90-watt cesium CL–2 source. From this one would conclude that the claim of 70 per cent efficiency in the region from 0.8 μ to 1.0 μ is excessive and that the true hololuminous efficiency in this region is about 20 per cent, like that of the cesium lamp.

The xenon lamp is said to be capable of electrical modulation up to very high frequencies, with carrier frequencies as high as 200 megacycles used in laboratory tests. The distribution of intensity among the spectrum lines is said to change with frequency at frequencies over 1 megacycle, and the wavelength of maximum intensity can be displaced at high frequencies as much as 0.5 μ. (Similar phenomena have been reported in the literature for other discharges.)

The source is designed to be started by a voice-operated relay. After the lamp starts the starting circuit is cut off automatically. The source is maintained by the r-f power even when not transmitting. With the present circuits it is apparently susceptible to being extinguished by overmodulation.

The source is the most interesting feature of the Touvet system. Its modulation at high frequencies indicates a time lag comparable with that in microflash lamps. If an appreciable fraction of its radiation lies beyond 1.2 μ, as claimed, it might be most valuable for intermediate infrared work, as discussed in Section 4.8.

Filters. The filters used on the system were ap-

parently similar in composition and spectral transmission curve to cellophane-based Polaroid filters of type XR3X41 but did not have quite so sharp a cutoff or so high a peak transmission as the latter. The difference may be due simply to aging of the French filters (see Chapter 2).

Optical System. The source has been used at the focus of a 24-inch diameter, 10-inch focal length, silver-backed glass mirror, and of a 36-inch diameter, 15-inch focal length, Stellite mirror. The beam width is about 25 to 30 degrees, depending on the system.

Transmitter Circuits. The transmitter electronic equipment consists of six panel units: a high-frequency exciter [TrA], a high-frequency modulator for the source [TrB], an audio-modulator with a high-gain input channel for a crystal microphone [TrC], a high-voltage rectifier power supply capable of delivering 1 kilovolt-ampere [TrD], a 2 kilovolt-ampere line-voltage stabilizer [TrE], and a connection panel.

The units appear to be of conventional design. Unit TrC contains a master oscillator feeding into an amplifier capable of delivering 40 watts of audio power. This is used for audio plate modulation of a stage in the exciter panel TrA, which in turn feeds two amplifier stages. The frequency response is flat to ± 1 db from 200 to 6,000 cycles. A 600-cycle and a 1,700-cycle oscillator for c-w modulation are incorporated in the amplifier. Unit TrD is of the condenser input full-wave rectifier type. Unit TrE was designed for test and measurement purposes, and therefore provides for manual adjustment of supply voltages and output power. It also contains voice-controlled relay circuits for automatic operation.

Receiver

Photodetector Cells. The resonant gas cell detector mentioned as being used with the original French equipment is said not to depend on selective absorption of the radiation. It is supposed to give twice the communication range obtained with a cesium phototube but is still in the developmental stage and was not used in the present equipment. The special design of tubular cell has been reported to be 20 centimeters long and 6 centimeters in diameter, with a cylindrical photosurface mounted along the cell axis; it is said to require 800 volts for operation. The nature of the photosurface was not disclosed, but it was said to be sensitive from the visible to 5.0 μ.

Apparently an ordinary silver-cesium vacuum phototube was used in the present equipment. The threshold for voice reception was computed to be about 5×10^{-10} watt input signal, but the receiver appears to be no more sensitive than that of type E, whose threshold is several times this. The reception angle of 2 degrees reported for the 18-inch focal length lens corresponds to an effective photosurface area of about 0.5 square inch.

Electronic Equipment. The receiver electronic equipment consists of four panel units, including an a-c and d-c power supply (ReA), an audio amplifier (ReB) to feed a high-speed telegraph recorder (if desired), a loudspeaker or earphones, and a connection panel; and the r-f receiver panel. Unit ReB delivers an output of 10 watts. A switch selects (1) one stage or (2) two stages of resistance-coupled amplification for telephony, or (3) a two-stage resonance choke circuit tuned to 600 cycles with a peak width of 80 cycles for telegraphy. In positions (1) and (2) the frequency response is flat to ± 1 db from 80 to over 6,000 cycles. A vacuum-tube rectifier provides d-c impulses for a high-speed relay.

Operational Tests

Three types of operations were conducted:

1. NDRC-Armed Services demonstrations over ½-mile range.
2. Study of reception of signal by type E receiver.
3. Range tests.

Demonstrations. With the source in the glass mirror, good intelligibility was obtained over a 1,000-yard range from the roof of Northwestern Technological Institute to Grosse Pointe Lighthouse with the receiver lens stopped down to a 3-inch square aperture. At the time of the official demonstration to representatives of NDRC, Army, and Navy on July 6, 1945, it was found that a small audio-frequency TF-cell receiver in the lighthouse picked up the voice communication very well although it had previously been understood that the Touvet system was to be secure against such reception.

To determine the seriousness of this defect, the

following tests were made with the Touvet source and the Touvet and type E receivers. The purpose of these tests was to determine definitely to what extent the Touvet transmitter could send voice or code without being received at all or without being received intelligibly by the type E audio-frequency receiver.

Type E Reception of Intelligence from Touvet Source. A type E receiver (of 14-inch aperture, using a TF cell) was mounted beside the Touvet receiver in the lighthouse. A Wratten 87 filter (with ehT of 0.80) was used over the type E receiver throughout the tests; no filter was used on the Touvet receiver excepted as noted below. The Touvet source on the roof of the Institute was filtered, but used without any reflector. The tests were in three parts, aimed at (1) sending code to the Touvet receiver and no signal to type E, (2) sending code to the Touvet and a steady tone to type E, and (3) comparing voice reception on the two receivers.

From the results of the tests it appeared that to accomplish objectives (1) and (2), the Touvet carrier frequency was being changed by the coding key from a value close to the superheterodyne frequency of the Touvet receiver to a value very different. The results were as follows: In test (1) the code was not received by the type E receiver, except for faintly audible clicks as the key was opened or closed, which might have permitted training the receiver on the bare source at distances up to a mile or on the complete transmitter up to several miles; in part (2) these clicks were not audible on the type E receiver, being drowned out by the steady tone superimposed on the carrier wave.

In part (3) both receivers gave good intelligibility, the S/N ratios being about the same for both. The limit of intelligibility was obtained on the type E receiver with the receiver aperture stopped down to 1½ inches diameter. As this is about the minimum aperture for reception from a bare CL–2 cesium source at this distance, the equivalent holocandlepower of the two sources measured on a TF cell must be comparable. The corresponding test of minimum aperture was not made with the Touvet receiver because it "would have necessitated certain changes in the adjustment of the receiver."

A strong d-c background light placed near the source raised the noise level in the Touvet receiver considerably; interposing a double layer of filter over the Touvet detector cell reduced the noise somewhat. The noise level of the type E receiver was only slightly affected by the background light.

The source was observed with a type C–3 infrared electron telescope during these tests, with results as reported above in "Security."

The conclusion from these three tests with the type E receiver is that the Touvet transmitter as at present constructed (1) probably has adequate system security against audio-receiver detection when unmodulated frequency-shift coding is used, (2) has no system security when modulated coding is used and no message security against audio reception when voice is used, and (3) has message security at all times, but no system security against image-tube detection.

Range Tests. Three tests were made with the Touvet system operating over a range of 5.6 sea miles between the roof of Northwestern Technological Institute and Montrose Beach in Chicago. The source was operated at 1.15 amperes r-f current in the Stellite mirror. (This mirror had a measured reflection coefficient of about 0.5, which may have decreased the range somewhat.) In the worst weather experienced on these tests, with atmospheric transmission about 0.4 per sea mile, code reception was reported as very good and speech reception was at or below threshold, fading in and out.

The mean vacuum voice range as indicated by the tests is of the order of 30 miles, and the ACW range for 100 per cent intelligible communication is about 6.5 sea miles.

Present Status

The one source tube in working order was purchased from Captain Touvet by BuShips in September 1945, and the one-way communication equipment (excluding the source tube) constructed under Contract OEMsr–1391 has been transferred by OSRD to BuShips.

It is understood that the necessary components to provide two-way communication are to be completed by BuShips and that the characteristics of the overall equipment, and especially the source, are to be further studied by Contract NObs–28373 with BuShips, which has superseded NDRC Contract OEMsr–990.

RECOMMENDATIONS

Because of the secretiveness and resistance to proper inquiry and supervision throughout the course of Contract OEMsr-1391, and because of the unsatisfactory condition of the equipment when it was transferred to BuShips, the first and most important problem is to reconstruct correctly the operation of the system and restore it to working order. The pattern of secrecy maintained in this case between the personnel of a contract and the sponsoring organization sets an unfortunate precedent and has led to unsatisfactory consequences. Future civilian scientific groups such as OSRD should take steps to prevent such situations from arising.

The xenon source has novel and unique properties for near and perhaps intermediate infrared work and should be studied carefully. The receiver has too narrow an angle of view for manual operation on shipboard. In its present form it would require a stable table and training system to be of any value for ship communication; a larger receiver angle could be obtained with no appreciable loss in range by use of different receiver optics and perhaps different phototubes. More precise information should be obtained on the other types of receiver cells described by Touvet.

Alteration of the method of modulation as suggested under "Evaluation" would give more message security.

4.6 POLARIZATION SYSTEMS

4.6.1 Types of Systems

Two systems have been devised in which the state of polarization of the radiation beam is varied by the modulation. Such modulation may be arranged to give negligible variation in the intensity of the emergent beam, so that an ordinary a-f receiver will receive no signal from the modulated source. In both systems this is accomplished by having the modulation vary only the distribution of energy between two coincident beams of complementary (incoherent) polarization which have the same total energy.

In either system, one arrangement is to have the two beams plane-polarized at right angles in which case the signal is received by eliminating one beam with a plane-polarizing analyzing sheet over the receiver. Or the beams may be circularly polarized in opposite directions in which case even such a receiver will get no signal unless a quarter-wave plate in the correct orientation is added to convert the beams to perpendicular plane polarization before they strike the analyzing sheet.

This second arrangement is more secure because in the first arrangement considerable analysis of the plane polarized beams may take place from water or earth reflections or haze scattering, producing a large percentage of ordinary intensity modulation in the beam. Also, plane polarizing sheets are now commercially common optical devices and are likely to be tried over a receiver by an enemy attempting to "break" a secure system, while large quarter-wave sheets are not yet so common or so easy to produce.

Systems like these are very inefficient compared with non-polarizing systems having an equivalent percentage of intensity-modulation of the source. Even with perfect polarizing devices 50 per cent of the light is lost in the initial polarization to create the two beams (unless a beam-splitting device can be used), and actual infrared polarizing sheets for the wavelength region from 0.8 to 1.0 μ transmit only about 35 per cent of the incident radiation. Further analyzer and reflection losses reduce the actual efficiency to less than 20 per cent of obtainable intensity-modulation efficiency.

One of the polarizing systems which has been devised uses simple audio-modulation of the polarization, while the other produces the polarization by a supersonic vibration which modulates the beam with an r-f carrier wave.

TYPE L

The first system, type L, began as a variant of type E and was studied under Navy contract by Baird Associates, Cambridge, Massachusetts. The principles will be presented only in outline form here as the study was not an NDRC project, although information on type E circuits and the use of the cesium source and TF cells was furnished to this company by Contract OEMsr-990. The two polarized beams were to be produced by two adjacent type E cesium lamp optical systems. These were to be covered by complementary infrared polarizing Polaroid sheets, plus infrared quarter-wave sheets for producing circular polarization, if desired. The total intensity was to be kept constant

by audio-modulating the two lamps in opposite phase, with special arrangements for keeping the amplitude of the intensity modulation of the two beams the same and for reducing second-harmonic distortion in the sources, which would give rise to overall intensity modulation. It was felt that intensity modulation could be kept within a maximum of the order of 5 per cent of the total beam intensity and that this amount would give a tolerably secure system.

Recent information furnished by courtesy of Section 660E, BuShips, indicates that the cesium lamps in this system are to be replaced by concentrated-arc lamps to give a narrow-beam system known as type L.

4.6.2 Photoelastic Shutter System [f]

DESCRIPTION AND PERFORMANCE

Course of Development. A second polarization system has been constructed by MIT Contract OEMsr-576, Project Control NS-187.[27,28,29] The polarization is modulated by the photoelastic effect in a block of glass strained by a standing supersonic wave. This system is an outgrowth of earlier work by the personnel assigned to this contract in attempting to adapt the Kerr cell for use in a polarization system. This work was not very successful because the amount of luminous or infrared flux controllable through the small aperture of feasible Kerr cells is quite limited.

Work on the photoelastic shutter was started in August 1942 at the request of the Army Air Forces and was continued under Project Control NS-187 for the development of a two-way system for Navy use. A complete two-way system was transferred to BuShips in the summer of 1944 to serve as the basis for the production of pilot commercial models.

General Design. The general design of the system is shown in Figures 28, 29, and 30. It consists of (1) a transmitter mounted on a tripod, containing (2) a 75-watt r-f modulator for (3) the photoelastic glass shutter or *modulator block,* which is illuminated through a Polaroid polarizer and a filter by the collimated radiation from (4) a 250- to 600-watt sealed-beam landing light. For two-way communication, each station must also have (5) a receiver, mounted on a tripod, containing (6) a 12-inch diameter collecting lens or mirror, which focuses light through an analyzing sheet onto (7) an electron multiplier tube, the output of which is detected by (8) an r-f receiver and audio amplifier, feeding either a loudspeaker or earphones.

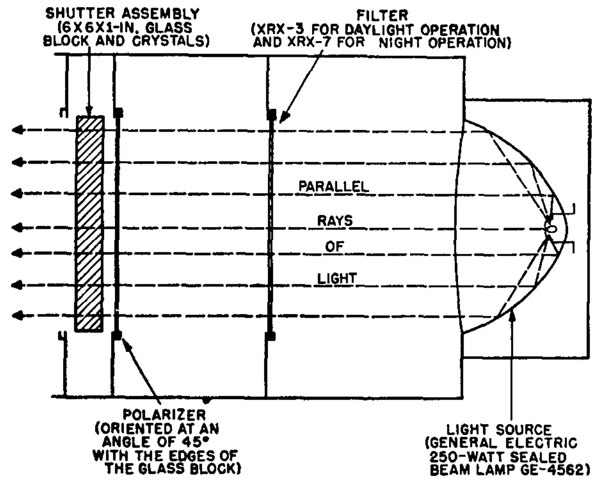


FIGURE 28. Photoelastic transmitter arrangement—"T-1 Panda."

The transmitter shown in Figure 29 is not the final design, which was completely enclosed, but an intermediate stage which shows more clearly the

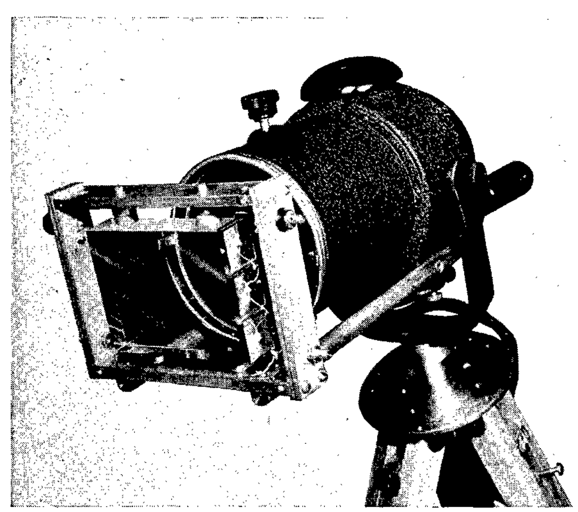


FIGURE 29. Arrangement and support of modulator block.

method of mounting and driving the glass shutter. Five types of landing lights can be used interchangeably but the best results were obtained with 7-inch diameter lamps, of 250 or 400 watts power.

[f] For list of symbols used in the equations of this section, see end of chapter.

When 600-watt lamps are used cooling of the filter and Polaroids is necessary.

The hpi beam width is about 5x5 degrees; a well-annealed spread lens could be used over the photoelastic block to increase the beam spread to about 12x20 degrees.

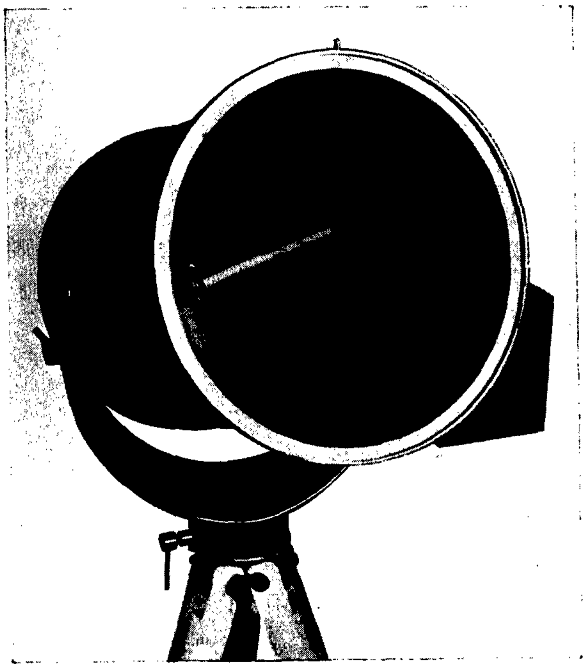


FIGURE 30. Photoelastic shutter system receiver.

In the final model, the glass modulator block is 6x6 inches in area and 2 inches thick and is made of optical crown glass.

The supersonic wave is set up in the block by a set of 12 X-cut quartz crystals 1 inch square and ⅛ inch thick attached to the top or side of the block. The crystals, their silver foil electrodes, and the block are soldered together by a special technique. The crystals are driven by a 75-watt radio transmitter at some resonance frequency which gives maximum light modulation. Many resonance frequencies are found for this system, spaced about 10 kilocycles apart between 300 and 2,000 kilocycles. In the final model, frequencies near 400 kilocycles were preferred, and crystals were cut whose natural frequency for longitudinal vibrations along the x direction was in this neighborhood.

The modulation response drops by 50 per cent from 100 cycles to 2,000 cycles audio frequency. This is probably the result of the decreasing response of the shutter system to sidebands above and below the resonance frequency. To compensate for this effect, higher audio frequencies are pre-emphasized in the transmitter so that the response is essentially uniform from 100 to 3,000 cycles.

The polarizing arrangement employed in the range tests is the "stripped" shutter whose method of operation is outlined in Figure 32. In this arrangement the polarizer consists of a series of strips, each strip covering the space between two nodal lines in the glass block. The strips have their polarization axes oriented at 45 degrees to the nodal lines, but the axes are alternately at +45 degrees and −45 degrees, each strip being oriented perpendicularly to its neighbors.

It will be shown below, under "Stripped Shutter," that such an arrangement produces an emergent beam from the block which changes from right to left circular polarization at just the r-f frequency, the total emergent intensity being constant at all times. The amplitude of the r-f variation in polarization is governed by the audio signal. This signal, therefore, not only cannot be received by any audio receiver but it cannot even be received by an r-f receiver if it is covered only by a plane polarizing sheet.

The receiver instead must be covered by an infrared quarter-wave plate followed by a plane polarizing sheet. The multiplier tube then receives an audio-amplitude-modulated r-f light signal which is converted to a-f and sent to headphones in the usual way.

Code may be sent either by using a 500-cycle oscillator built into the transmitter, or simply by on-off interruption of the carrier wave, with superheterodyne reception.

The receiver in the final model differs somewhat from the intermediate stage shown in Figure 30. It consists of a Farnsworth 6-stage infrared-sensitive electron multiplier mounted behind an iris diaphragm at the focus of a 12-inch diameter, 18-inch focal length lens. The circular analyzer sheets are placed over the lens. The multiplier output stage is part of an L–C circuit tuned to the r-f carrier frequency. The coil is inductively coupled to the antenna of a standard Navy type radio receiver. The hpr width of the receiver field is about 2 degrees.

Early models of the transmitter and receiver weighed about 30 pounds each, exclusive of tripods; the final models are somewhat heavier. The power supply and modulator amplifier are in a separate

8x10x16-inch cabinet. The receiver was designed to operate either from 110-volt 60-cycle a-c supply, or from 6-volt battery Vibro-Pack units.

Security. Polaroid filters of types XR3X–61 to XR3X–74 were used with the final units. These would give excessive NVR values, up to ¾ mile, with the 600-watt landing lights, except for the additional filtering action of the Polaroid infrared polarizing sheets which reduce the NVR to less than 300 feet for these lamps.

The transmitter is electrically shielded to prevent radio reception at distances greater than 200 feet.

The transmitter can be observed by an image tube in the beam, but neither voice nor code modulation can be detected by such a tube. No ranges have been measured for such detection, but very rough estimates based on image tube experience with type E indicate ACW image tube ranges up to perhaps 8 sea miles.

The transmitter in its final form cannot be detected by any audio-frequency receiver. It can be detected only by a tuned r-f receiver which is covered by a quarter-wave plate and plane analyzer. This system therefore has the greatest message and system security of any NIR system developed by NDRC.

Range. Apparently no attenuation measurements were made during the field tests on the system, so the observations cannot easily be reduced to standard conditions, but the consensus of results indicates an ACW range of about 4 miles, using a 450-watt lamp, an 8x20-degree transmitter beam, and a 2-degree receiver angle of view. This range corresponds to a vacuum range of about 12 miles. On one occasion, with the 450-watt lamp and a 5x5-degree hpi beam, good reception was obtained at 7 miles range.

Evaluation. The photoelastic shutter system is simple and ingenious and, as will be seen below, it can be easily changed into variant forms which are secure even from each other. Nevertheless the highest modulation efficiencies obtainable are estimated to be about 5 per cent, as compared for example with 25 per cent for even the cesium lamp polarization system (see Table 2). In fact, this shutter system has the lowest modulation efficiency, and therefore the lowest range for a given lamp power, of any of the systems discussed here.

On the other hand, because of the simplicity of its modulation method, very little power is required beyond the lamp power, and the range attained for a given *total* power is comparable to that of the other systems. Weight and bulk also appear to be favorable, as far as laboratory models give an indication on these matters; but perhaps the best feature of the system from a military point of view is that its large components—the landing lights, and the standard 75-watt transmitter and r-f receiver—are all standard units. These advantages, combined with its high security and with the possible simultaneous use of several r-f channels as mentioned in the beginning of Section 4.5, make the photoelastic system decidedly worth further military development.

Transmitter

The elucidation of the possible states of polarization of the light beam and the theoretical determination of the audio-frequency variation of the mean transmitted flux as a function of the supersonic intensity are both very pretty problems.[28] Some of the simpler results will be outlined here.

Comparison with Optiphone. In passing, it may be mentioned that from one point of view (which we will not adopt in what follows) the shutter works essentially on the same principle as the supersonic shutter in the Scofoni system used in the optiphone (Section 4.5.1). In both systems the supersonic strain produces a periodic spatial variation of the optical properties of the medium, creating a diffraction grating. The amplitude of this variation determines the intensity of light in the different orders of diffraction.

In the Scofoni narrow-beam system, these orders are spatially separated. The photoelastic shutter system uses a wide beam in which they all overlap, but the various orders are differently polarized and may still be partially separated by an analyzer.

Optimum Conditions. The variation in the state of the polarization is produced by the variation in the birefringence (double refraction) of the glass which is in turn the result of the varying supersonic strain. There exist certain conditions for obtaining maximum birefringence for a given input supersonic energy.

First, the birefringence is greatest for a *longitudinal* supersonic wave. In such a wave, the optical axis of the strained glass is parallel to the direction of propagation and perpendicular to the nodal

planes. For a maximum effect the polarizer must be oriented at 45 degrees to this axis, and the analyzer parallel or perpendicular to the polarizer. For uniform behavior over the whole surface of the block the optical axes must be everywhere parallel, which means that the nodal planes must be parallel. This is practically possible only in rectangular or square blocks in which the supersonic wavelength is short compared to the dimensions of the block.

The polarized light incident on the strained glass is divided into two components, one vibrating (at *optical* frequency) parallel to the optical axis, and the other perpendicular to it. There is a difference $\Delta\mu$ in the refractive indices of the glass for the two components and as a result one lags behind the other by a phase shift ϕ after passing through the thickness t.

$$\phi = 2\pi \frac{\Delta\mu}{\lambda} t, \tag{11}$$

where λ is the wavelength of the light. If the analyzer is crossed with the polarizer, the intensity transmitted through it is then

$$I = I_0 \sin^2 \frac{\phi}{2}. \tag{12}$$

In this system, λ is limited to the near infrared. The thickness t used in tests was ½ inch to 2 inches, being limited by the transmitter energy and quartz crystal sizes available and by the nonuniformity of larger blocks. Some tests, which appeared rather promising, were made with one surface of the glass block silvered so that the light was reflected back through it and the effective thickness was doubled.

The value of $\Delta\mu$ is proportional to the difference $(p - q)$ of Neumann's photoelastic constants, which depends on the material of the block. Plastics have the largest difference but give excessive damping. Various glasses were tried and were all found to be very satisfactory except Pyrex. The principal requirement for the glass is that the index of refraction be low, preferably with n_D below 1.55. Fused quartz would be excellent, because of its low index, large value of $(p - q)$, and small damping, except that the damping is so small that the resonance points are extremely sharp and so there is no response to the voice-modulated sidebands! The power requirement for ordinary glasses is about 0.1 watt per cubic inch for shutter operation but that for quartz is 10 to 50 times lower. A suitably uniform block of fused quartz prepared by the General Electric Company proved excellent for code transmission. It is thought that external mechanical damping could be used to improve the voice response of quartz blocks while still keeping an extremely low transmitter input power. The value of $\Delta\mu$ is also proportional to the quantity a/l, where a is the supersonic amplitude and l is the supersonic wavelength in the glass. These factors are determined by the input energy and by the kind of quartz driving crystals which are suitable.

The input energy may not be increased indefinitely but instead should be carefully limited for optimum performance. The maximum possible intensity change at any point is produced by varying ϕ from 0 to 180 degrees. The maximum time-average intensity over the whole block is obtained if certain points have higher values of ϕ (up to 300 degrees) for limited intervals, but any increase of supersonic amplitude beyond this point causes a *decrease* of transmitted light intensity.

This optimum energy corresponds to supersonic amplitudes of vibration of the order of 10^{-5} to 10^{-6} centimeter in the glass, which is of an order of magnitude frequently attained in supersonic studies. However, normal operation is best with even lower amplitudes because of strong nonlinearity with high phase-shifts and because of excessive heating of the block, which introduces spurious birefringence.

Uniform Shutter. The simplest case is that of a polarizer which is uniform over the whole surface of the block (hereafter called a "uniform shutter") as indicated in Figures 31 and 32. The polarization of the light passing through the nodal planes (planes of no strain) is unchanged by the block. The emergent radiation which has passed through the antinodes is polarized elliptically, rotating in one direction through a region of expansion and in the other through a region of compression. If the phase shift is 90 degrees the ellipses become circular; if it is greater the long axes become perpendicular to the original orientation and, when the shift becomes 180 degrees, the light becomes linearly polarized in this perpendicular direction.

The light beams passing through adjacent antinodes are far enough apart spatially that they are incoherent, that is, the phase relations between them are not fixed but are changing randomly. The addition of the incoherent ellipses of opposite directions of rotation is equivalent to the addition

of two incoherent linearly polarized beams, one polarized along the major axis of the ellipses, one along the minor. The effect of the supersonic strain is then to change the distribution of energy between these two linearly polarized beams (A and B in Figure 32).

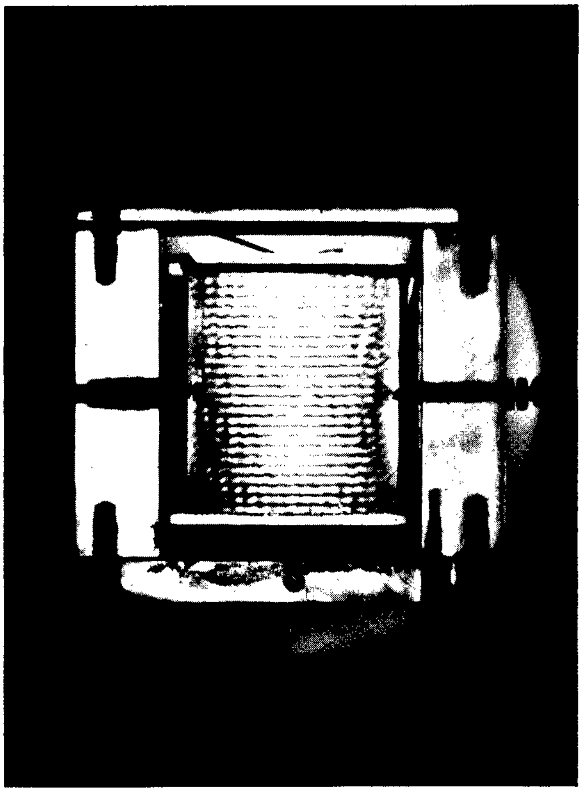


FIGURE 31. Appearance of vibrating block between crossed polarizers.

In fact not only plane-polarized light but incident light of any uniform elliptical polarization with these major and minor axes may be used. It is converted by the strained shutter into one beam of emergent light of exactly the same ellipticity, but smaller intensity, and a second incoherent beam of complementary ellipticity.

The intensity in beam B is zero at time $t = 0$ when the strain is zero; it increases in each half of the strain wave, whether the strain is positive or negative. From this result we can draw three important conclusions. First, the r-f frequency in the emergent beam is *double* the supersonic frequency and an r-f receiver must therefore be tuned to the double frequency. Second, the average intensity in beam B depends on the peak supersonic intensity so that if the latter is audio-modulated a strong audio component will be present in the emergent beam. (This component was used in early range tests.) Third, the instantaneous intensity in beam B is an *even* function of the strain, and therefore is nonlinear and gives only very small effects for small strains.

The phase shift as a function of position on the block is evidently $\phi_m' \cos\theta$ where ϕ_m' is the maximum optical phase shift at the antinodes and θ is the phase angle in the supersonic wave. Using equation (12) we may find the instantaneous average transmitted intensity in beam B per unit area as a function of ϕ_m'. It is only necessary to integrate from $\theta = 0$ to $\theta = \pi/2$, because of symmetry.

$$I = I_0 \frac{2}{\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} \sin^2\left(\frac{\phi_m'}{2}\cos\theta\right) d\theta$$

$$= \frac{I_0}{2}\left[1 - J_0(\phi_m')\right], \qquad (13)$$

where J_0 is the Bessel function of order zero. Here I_0 is the maximum transmission through the Polaroids when they are parallel—about 20 per cent of the incident intensity, for existing infrared Polaroids, as noted above.

The intensity in beam B, averaged over an r-f cycle, is then

$$I_t = \frac{1}{2} I_0 \frac{2}{\pi} \int_{\alpha=0}^{\alpha=\frac{\pi}{2}} J_0(\phi_m \sin\alpha)\, d\alpha$$

$$= \frac{1}{2} I_0 \left[1 - J_0^2\left(\frac{\phi_m}{2}\right)\right]. \qquad (14)$$

Here ϕ_m is the peak optical phase shift reached at an antinode during the cycle. The variable of integration α is the phase angle of the time variation in the supersonic wave.

From this equation, at a value of ϕ_m of about 300 degrees, I_t reaches a peak value of about half I_0. Thus in audio modulation the maximum possible crest-to-trough value of the audio component is about 10 per cent of the intensity of the beam before polarization. If the modulation is restricted to the linear part of the curve represented by the last equation the fraction is less. In practice, because of the introduction of nonuniform stresses from heating, because of the frequent appearance of

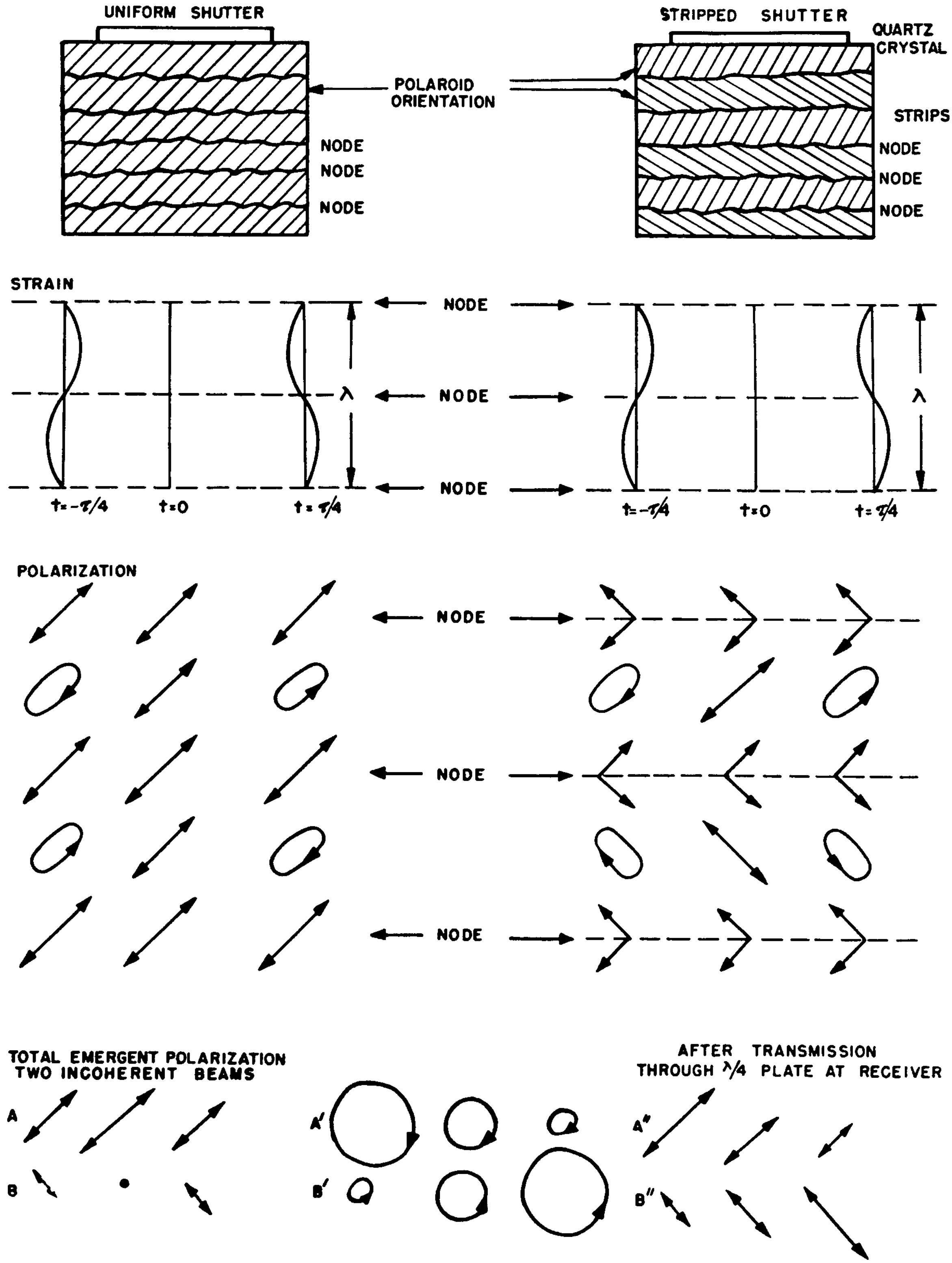


FIGURE 32. Polarization from photoelastic shutter.

a second set of dark nodal planes perpendicular to the primary set (see Figure 31), and because the light may pass through the shutter at angles up to 10 degrees from the normal, the maximum value reported has been about 5 per cent.

An interesting method was worked out for evaluating the optical phase shifts attained with a given supersonic input. These were determined by "uncrossing" two Polaroids (with the supersonic energy turned off) by an angle β until the transmitted intensity just matched the average intensity through exactly crossed shutters with the given input. The value of I_t is $I_0 \sin^2 \beta$, and φ_m can then be found from equation (14).

The attainable values of light-current modulation ratio are near 1.5 on the linear part of the curve, for low-frequency audio variations, as is predicted by equation (14). Because of the drop in response away from the resonance point, the values fall with increasing frequency of audio modulation, from about 0.8 at 100 to about 0.3 at 2,000 cycles per second.

The value of I_t in equation (14) is approximately the amplitude of the double-frequency r-f component of the light.

Stripped Shutter. Because of the drawbacks of the uniform shutter which were already mentioned —small output at low amplitudes, plane polarization, and audio modulation—an exhaustive examination was made of other methods of utilizing the double refraction. The most satisfactory is the stripped shutter, indicated in Figure 32. In this arrangement, alternate antinodes of the supersonic wave are covered by complementary Polaroid strips, oriented first at +45 degrees, then at —45 degrees, then at +45 degrees, and so on. For this case the polarization ellipses all have the same direction of rotation at a given instant, but half their major axes are at +45 degrees, half at —45 degrees. The total resultant beam is equivalent to two incoherent circularly polarized beams (A' and B' of Figure 32). A is more intense than B in one half cycle, less intense in the other. At $t = 0$, when the strain is zero, the light is unpolarized, that is, A and B are of equal intensity. When a quarter-wave plate is placed over the receiver, these circular beams are converted to the plane polarized beams A'' and B'', one of which is then transmitted through the plane analyzer to the receiver.

With the stripped shutter the beam reaching the receiver is then stronger in one half cycle and weaker in the other. In this case, then, the received r-f frequency is *equal* to the supersonic frequency; the average intensity is independent of the supersonic amplitude, and no audio modulation is detectable; and finally, the intensity is linear in the strain and therefore is larger than with the uniform shutter for small strains. This method has all the advantages the other one lacks. Because of the linear feature, much less driving energy (in experiments, only ¼ as much) is needed to obtain the same signal at the receiver with ordinary signals; however, the uniform shutter theoretically becomes superior with very high signals.

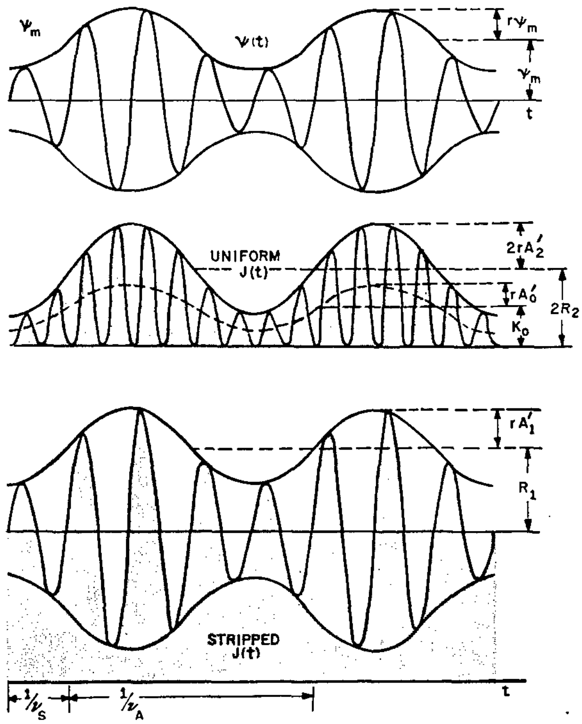


FIGURE 33. Comparison of analyzed modulation from stripped and uniform shutter.

This stripped shutter is extremely secret, as it has the advantages of both circular polarization and absence of audio modulation. The kinds of signal produced by the two types of shutter are compared in Figure 33.

The numerical expression of the intensity in A'' and B'' as a function of the supersonic amplitude has been evaluated only as a power series [28] and will not be given here.

One other variant method of modulation has been proposed. This consists of the use of a steady super-

sonic carrier which is audio modulated by *mechanical* vibration of the stripped shutter. In this method, the boundaries between the strips are not placed at the nodes but at the antinodes. The signal produced is similar in character to that produced by the ordinary stripped shutter method outlined above, but the mechanical method would not be as efficient.

Glass Blocks. In early laboratory models glass blocks ½ inch thick and 1½x1½ inches in cross section were used. An increase of area was made necessary by the deterioration of the strongly absorbing NIR polarizing and filter sheets under strong radiation intensity. By distributing the light flux over a larger area and by employing air cooling from a motor blower it was possible to secure continuous operation with 600-watt light sources. The use of larger shutters also greatly simplified the optical system and permitted the use of the standard landing lights.

Increase of the thickness of the shutter improves its efficiency. A doubling of the optical effects can be effected either by doubling the thickness of the block or by doubling the amplitude of vibration. The latter requires doubling of the voltage on the driver crystals and hence increases the power by a factor of 4; doubling the thickness only doubles the power requirement. The use of thicker blocks makes it possible to operate at lower voltages and thus avoid corona and the danger of electrical breakdown in the crystals. A drawback in using thicker plates is that thick commercial glass plate is not sufficiently strain-free for this purpose and the shutter must be made of well-annealed optical glass.

The blocks are ground and polished with opposite sides parallel within 0.001 inch. The photoelastic behavior of one block can be reproduced quite accurately by another block of identical dimensions.

Driving Crystals. The several X-cut crystals attached to a given shutter are of course matched. All crystals are attached with the directions of their polar x axes in the same orientation (that is, perpendicular to the face on which the crystals are soldered); the y axes are 90 degrees apart in neighboring crystals. The mosaic covers a small side of the shutter, thus for a 6x6x2-inch block, 12 crystals of 1x1-inch area are used in two rows of 6 crystals each.

The shutter operates best at a frequency close to the resonance point of the longitudinal vibrations of the driving crystals in the x direction, or close to an odd harmonic of this frequency. When soldered together the system of glass and crystals has a new set of resonance points which are much closer together than those of the crystals alone. Several active frequencies (that is, frequencies useful for the photoelastic work) of the shutter can be found near each frequency of the crystals. In fact, the shutter can be operated at a very large number of carrier frequencies distributed over a large range from about 100 kilocycles to 100 megacycles, but those near a resonance point of the crystals are easier to excite.

The driving potential of the crystals is 1,000 to 2,000 volts, requiring a thick crystal, about ⅛ inch, and consequently a fundamental frequency below about 3 megacycles, in order to avoid corona breakdown. In order to have several nodal planes in the glass block, so that they will be straight and parallel, frequencies above 0.3 megacycles are necessary. However, observations have been made with frequencies from 100 kilocycles to 15 megacycles.

In early tests a frequency of nearly 2 megacycles was used, but later, with thicker glass blocks, a frequency near 900 kilocycles was used so that the nodes would be separated farther. The radiation beam passing through the shutter then does not have to be so closely parallel for effective operation as it does when the nodes are close together. When the stripped shutter was used, it was found that even at this frequency too much light was crossing from one antinode region to the next in traversing the block, with a resultant serious loss of modulation efficiency. Consequently, the nodes were separated still farther in the final model by use of a still lower frequency, near 400 kilocycles.

The energy transmission from the crystal to the glass is considered to have been rather inefficient in these models. If this could be improved, lower powered transmitters would be adequate for complete modulation.

Soldering Quartz and Glass. No satisfactory cement for joining the quartz and glass was found. Many cements were tried but all were heated by the high frequencies and set up thermal strains; some failed to transmit the sound waves after a time.

Soldering the crystals to the glass was therefore tried and proved quite successful, although it is a delicate operation. The process worked out[29a] ap-

pears to be fairly novel and valuable and an outline of it will be given here; the interested reader should consult the original report for details.

First, the crystal and glass are given a thick coat of silver by evaporation in high vacuum. Then they are placed together with a 0.001-inch layer of rose metal between, and heated judiciously by a hot plate until fusion occurs. A glycerine solution of tartaric acid at the proper concentration is used as flux. The silvered surfaces act as electrodes for the crystals and leads may be soldered on with a soldering iron.

The copperplating process recently developed by Corning Glass Works might be a substitute for the silverplating in this method.

Oscillator. The driving oscillator is a single-tube circuit, operating normally at 1,500 volts with 75-watt plate dissipation. The constants of the tank circuit are carefully matched to give the maximum potential and energy transfer to the crystals which are connected in parallel with the tuning condenser. The audio modulation is effected by screen grid modulation.

A special feature of this oscillator is frequency control by acoustic feedback. A single quartz crystal is attached to the shutter on the narrow side opposite to the driving crystals. Vibrations in the glass are transmitted to this crystal and create an emf which is amplified and controls the grid of the oscillator tube. Thus the shutter automatically controls the frequency of the oscillator, and the driving frequency follows the small drifts of the mechanical resonance frequency of the shutter occurring during continuous operation as the result of temperature changes.

In the final models, the driving oscillator is housed in a small cabinet attached below the optical unit.

Monitor. For control of the transmission at the sender, a small fraction of the light is intercepted by a mirror, ½x½ inches in area, which sends the light to a photocell and amplifier. An output meter and telephone serve to record the intensity and quality of the light transmission. The circuit of this monitor is analogous to that used for audio reception in the receiver. This monitor unit is also mounted in the cabinet below the optical unit.

Receiver

The receiver consists of three parts: the optical system, in which the light is collected by a photodetector cell, the radio receiver, and a voltage supply for the detector cell. The latter two are in a separate cabinet and are of standard design and construction.

In early tests the optical system consisted of an 8-inch diameter concave mirror which focused light on an infrared-sensitive gas-filled phototube which was suitable for use with the uniform shutter and audio reception being used at that time.

Later, for r-f reception, a Farnsworth 6-stage infrared-sensitive electron multiplier was used. A 12-inch diameter, 18-inch focal length glass lens was used as the collector, because the field could then be stopped down with an iris diaphragm to improve daylight communication.

An optical system with such a low f/number necessarily has a narrow angle of view, here about 2 degrees. The width of this angle could be approximately tripled, with no loss in sensitivity, by returning to a mirror system; the narrow-angle system is valuable only for daytime work.

Variable Quarter-Wave Plate. One of the most interesting and scientifically valuable results from Contract OEMsr-576 was the discovery of methods of duplicating the action of a quarter-wave polarizing plate by using two or three plates having phase differences different from a quarter wave.[28] Two such plates, for which the phase differences are anywhere between one-eighth wave and three-eighths wave, when placed together in proper orientation, will convert a particular orientation of plane polarized light into circularly polarized light. Thus two plates which are each quarter-wave plates at just 0.6 μ may be used together to serve as a quarter-wave plate for any wavelength between 0.4 μ and 1.2 μ. Such combinations were used by this contract over the receiver in early studies before infrared quarter-wave plates became available.

The combination of two phase-difference plates does not behave identically like a quarter-wave plate for light of all orentiations; but a combination of *three* arbitrary phase-difference plates may be made to do so.

Operational Tests

All field tests were carried out between fixed stations, one unit being in the tower of the Blue Hill Observatory and the other at one of five receiving stations at distances of ¾, 1⅝, 2⅛, and 7⅓

miles away. Tests for two-way communication could be made only over the 2⅛-mile range because none of the other stations could be supplied with a-c power for the transmitter. From the S/N ratios observed on a given test at a given station, the threshold ranges of the equipment used could be estimated. Unfortunately, no attenuation estimates seem to have been made on these tests, and the reduction of the results to ACW or vacuum conditions is very uncertain.

Part of the light path to all stations is over water, and the resulting differential thermal convection currents were held to be responsible for excessive "twinkling" and loss of intelligibility observed in some tests on clear quiet nights.

Altogether, four separate transmitting and receiving units were constructed. Following an early system which had 1½-inch square modulator blocks, cemented crystals, and audio transmission, a second system was built. This had a soldered shutter of 4x6x¾ inches, driven by four crystals at 920 kilocycles from a standard 75-watt Hallicrafter radio transmitter the tank coil of which was inductively coupled to an L–C circuit in which the crystals formed the capacity. Field tests in March 1943 showed satisfactory voice communication with this system over a range of 1⅜ miles, with an 8-inch receiver mirror, a multiplier phototube, and a two-stage amplifier.

Early Demonstration. The first instrument to have most of the features of the final unit was demonstrated to representatives of the Armed Services and of NDRC on May 10, 1943. The transmitter used a 250-watt landing light, a 6x6x1-inch shutter oscillated at 912 kilocycles with feedback control, and a 12-inch receiver mirror, a multiplier phototube, and a 4-stage audio amplifier. The hpi and hpr widths were about 5 degrees. Satisfactory daylight transmission with XR3X filter was obtained at 1⅝ miles, while night transmission with XR7X filter was demonstrated at 2⅛ miles. Under favorable weather conditions good voice communication was also obtained with this system over the 3⅜ mile range. This transmitter has been operated for some 2,000 hours over 18 months without alterations of the electrical equipment or change of the soldered shutter characteristics. Some soldered-on shutters have been operated continuously at full power for 12 hours without any decrease of transmission.

Final Units. Later this unit was modified for use with a 6x6x2-inch stripped shutter for 400 kilocycles single-frequency r-f transmission with a spread lens for 12x12-degree beam spread. The receiver was altered to have a circular analyzer, 1-inch lens, and a radio receiver.

A final and rather elaborate new system, containing several auxiliary features to facilitate test and measurement, was completed in November 1943. This provides for quick interchange of components such as lamps, shutters, filters, and lenses, but is otherwise much as described above under "General Design." A variable and a 500-cycle audio-frequency oscillator were incorporated in the transmitter. Tests with this system formed the basis for the redesign of the previous system just mentioned.

The S/N ratio was found to be increased sevenfold by r-f reception compared to audio reception. For code, on-off interruption of the carrier wave gave much greater ranges than did low-frequency code modulation of a continuous carrier wave.

Tests showed that the use of a stripped quarter-wave plate is practicable and gives the same results as the use of stripped plane-polarizers, as was expected from theoretical considerations.

With a 250-watt lamp, 12x20-degree hpi beam, and XR3X–60 filter, a 4-mile range is attained in all but the worst weather. With a 450-watt lamp, and 5x5-degree beam, a 7-mile range was attained on one occasion; at other times only slowly spoken words were intelligible at this distance.

Present Status

The two final systems just described constitute sufficient equipment for two-way voice communication. Upon request of BuShips these two systems were turned over to that group in July 1944 to serve as the basis for the production of pilot commercial models. Such pilot models were subsequently built by White Research Associates, Cambridge, Massachusetts.

Recommendations

This photoelastic shutter system is now well past the laboratory stage and requires only tests against other systems to determine its comparative military value. The performance of the shutters has now been carried to nearly the maximum which is pos-

sible with present materials, according to a rather completely developed optical theory which is itself of great interest. The modulation method per se is inherently inefficient, but the total power consumption appears not to be excessive compared to other NIR systems of similar range. The system is ingenious and simple and has the great advantages of good secrecy, choice of r-f channels, and the use of standard lamps, radio transmitters, and radio receivers.

Better NIR polarizing sheets would be desirable for such systems. The use of fused-quartz shutter blocks deserves further study. A wider receiver angle would probably add to the military value of the system.

4.7 PROPOSED SPECTRAL MODULATION SYSTEM

Very recently another voice modulation system has been proposed [18b] based on the use of radiation. It consists of a series of narrow-wavelength bands in the infrared, modulation to be accomplished by simultaneous shifting of the wavelengths of all these bands, first to longer wavelengths, then to shorter, then to longer, etc., by means of a vibrating-mirror arrangement. The security of the system lies in the fact that the intensity of the beam remains sensibly constant and no photosensitive receiver can receive the signal unless equipped with a suitable device to convert the spectral modulation into amplitude modulation.

Transmitter. The method of modulation is shown in Figure 34. The light from a continuous-spectrum source, such as a tungsten lamp, is spread by a dispersing system into a spectrum. This falls on a grid of alternate opaque and transparent lines, which permit selected wavelength bands to pass. These are reunited into an achromatic beam by a second identical dispersing system. A vibrating mirror between the first dispersing element and the grid is used for audio modulation of the wavelengths passed.

A number of transparent grid lines, probably at least six, must be used with this system. If one or only a few wavelength bands are transmitted, their motion in the spectrum will be converted to amplitude modulation in *any* receiver if they happen to fall at a point where the slope of the detector response curve or the slope of a receiver filter spectral transmission curve is very steep. The magnitude of this effect decreases with increase in the number of wavelength bands used. To avoid such an effect the German spectral-modulation blinker systems (Section 4.2.1) employed modulation of a narrow *dark* band in the spectrum, *not* modulation of narrow bright bands.

No filter over the source would be needed with the present spectral modulation system since the grid can be used to cut off the spectrum at any desired wavelength.

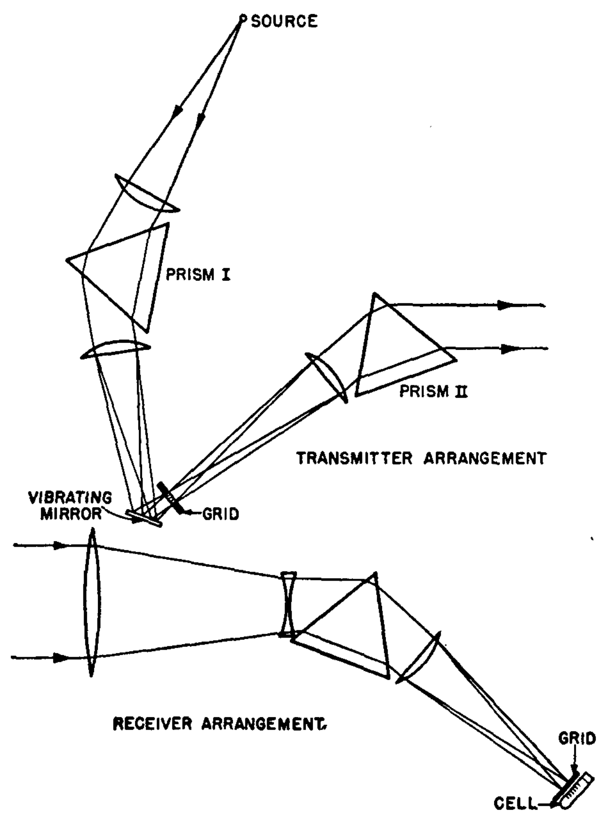


FIGURE 34. Spectral modulation system.

For highest intensity the width d of the source (or entrance slit) should be approximately equal to the width of the grid lines. The smallest possible beam width is then d/f, where f is the common focal length of the three lenses. In the system shown the emergent beam varies in direction slightly during modulation by an angle somewhat smaller than d/f. The beam width used should be, therefore, several times wider than d/f, so that this oscillation will not interfere with reception. The

width may be obtained by defocusing the last lens or by use of a "beam spreader" device.

Receiver. Reception of the signal is obtained by use of an identical dispersing system and identical grid over the photodetector, so that, as the wavelength bands of the incoming light vary, they move across the grid and the light transmitted through the grid to the photodetector is amplitude-modulated.

Security. If the grid over the photodetector has the wrong spacing or line width, a great loss in range results so that the system has message security against interception even by an enemy receiver of the same kind unless the grid of the latter system is of exactly the right design. Without difficulty the source and receiver grid spacings on all systems could be occasionally changed to make interception less easy.

Modifications. Multichannel communication is evidently possible, each channel having a different grid spacing. Several interchangeable grids could be placed on source and receiver for channel selection. The number of noninterfering channels on a feasible system is not large, perhaps less than half a dozen.

Several variants are possible in the source modulation system. In one, the grid might be made to move. It seems unlikely that this could be made efficient because the amplitudes of mechanical translation which could be obtained easily at voice frequencies are of the order of a few thousandths of an inch while the line width d required for ease of adjustment would be several times this, making the modulation ratio small. Another variant would be to use the vibrating-mirror system but dispense with the second dispersing system, reflecting the desired wavelength bands back through the first system by a reflecting grid. The returning beam could then be reflected in the desired direction by a semitransparent mirror, but at some loss in efficiency. Both these variants have the advantage that the emergent beam would not oscillate in direction with the modulation, and therefore it could be reduced to the minimum width d/f.

Evaluation. The system can be made from commercially available components. It is only slightly more complex than ordinary vibrating-mirror systems and may be almost as efficient. The proposal deserves further study as a supplement to such systems.

4.8 POSSIBLE INTERMEDIATE INFRARED [IIR] COMMUNICATION SYSTEMS

General Possibilities

Scope of Work to Date. Other types of infrared voice communication systems can now be devised which use radiation in an entirely different wavelength region to carry the communication. This region is the intermediate infrared between 1.4 and 6.0 μ. It lies beyond the 0.8 to 1.4 μ region involved in the near infrared systems previously discussed. Such IIR systems have been made possible by the invention of the lead sulfide photoconductive cell, the first sensitive detector of radiation beyond 1.4 μ to have a response time short enough to pick up audio-frequency signals.

Considerable space will be devoted at this point to the possibilities of the IIR. This will be done, first, because it is an important region, the exploiting of which will almost double the military usefulness of the infrared for communication, since every NIR system has in principle an IIR counterpart, to say nothing of the value of the region for purposes of heat detection (Chapter 9); second, at this time, IIR systems are just entering the laboratory and development stage, and many mistakes and false hopes may be avoided by a clear understanding of the relative advantages and limitations of, and the unique conditions imposed on, work in the IIR.

The discussion is based on survey measurements and preliminary calculations made under Contracts OEMsr-60 (Harvard University), OEMsr-990 and OEMsr-235 (Northwestern University).[19,32,33] The object of this work was to examine the feasibility of IIR systems and to investigate suitable sources, methods of modulation, filters, atmospheric transmission, and expected ranges. The termination of the war interrupted this work before an IIR voice communication trial system was actually built, so the conclusions here must be regarded as very tentative. Further work on the same lines and construction of trial systems for military use is highly recommended.

Advantages of the Region. By using radiation in the IIR, with the visible and NIR radiation eliminated by filters, a communication system can be made which has, at present, excellent system security, i.e., which is secure against enemy detection

by any present infrared electron telescopes or by phototube or TF-cell receivers. The only detectors for such a system known to the enemy would be the German PbS cells or other longer wavelength cells as yet incompletely developed. This comparative security may not last long, but in any case a new and independent channel of communication has been opened up and should be utilized.

Disadvantages of the Region. A possible disadvantage of IIR communication, the importance of which cannot yet be assessed, is the sensitivity of the PbS cell to low-temperature heat sources (such as engine exhausts in its field of view), as a result of its long wavelength response. The noise produced in a receiver system by such sources may prove troublesome.

Enemy Use. The German Lichtsprecher systems (Section 4.3.1) have for several years used PbS-cell receivers with a tungsten source. The effective communication wavelengths lie in both the NIR and IIR. The systems operate with beams of about ¼ degree and are probably sufficiently secure without elimination of the NIR. If necessary, the NIR could be removed by a suitable filter with little loss in range.

Lead Sulfide Cells as IIR Detectors

Properties. The lead sulfide photoconductive cell, developed in America under Contract OEMsr–235, is described in Chapter 3. Its use as an NIR detector is discussed under "Daylight Operation," Section 4.1.3, and as a detector of heat sources in Chapter 9. The properties of the cell already mentioned as important for voice communication work are (1) insensitivity to background light, (2) gain in sensitivity at low temperatures, and (3) flat frequency response. The additional property important for the IIR is (4) its response to wavelengths extending from the visible to beyond 3 μ. Two fairly typical response curves are shown in Figure 35A.

Other types of cells sensitive to even longer IIR wavelengths have been produced by the same contract but not in quantity (Chapter 3). Their properties have not yet been examined as carefully as those of PbS. They will therefore not be considered here, but they deserve much further study as IIR detectors.

Sensitivity. Unfortunately, the most sensitive PbS cells yet produced have S/N ratios averaging about 25 db lower than TF cells of the same size for the same modulated input energy of wavelengths in the sensitive range. This is not so serious as it would seem, if a continuous-spectrum source is used, because a much larger fraction of the radi-

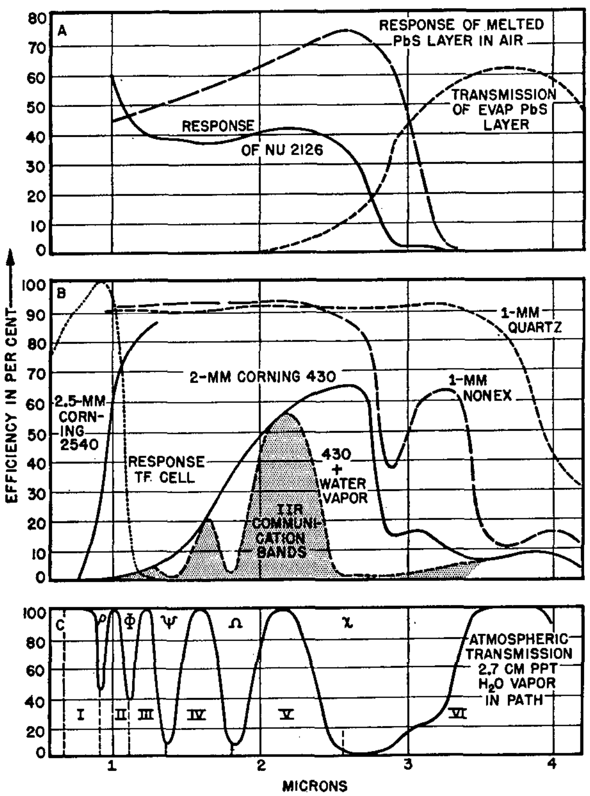


Figure 35. Response of cells and transmission in the IIR.

ated energy is emitted in the wide wavelength response band of the PbS cell than in the narrow one of the TF cell. For a tungsten lamp source at 2848 K, covered by 2.0 millimeters of Corning 2540 filter, the PbS S/N ratio is only 10 db less than the TF S/N ratio (20 db if no filter is used). If the lamp temperature were reduced to about 1500 K, keeping the same filter, the PbS value should become some 15 db better than the TF value. These figures are for a 90-cycle signal. Presumably the relations remain approximately the same at the speech frequencies near 1,500 cycles which are important for intelligibility since the S/N ratios are independent of frequency (see Chapter 3).

The PbS cells are still very new, and their sensitivity may be greatly increased with further development.

Area. Most of the PbS cells produced under Contract OEMsr–235 have had sensitive areas ¼ inch square or smaller, suitable for use in narrow-beam systems; but one or two cells have been made fairly successfully with areas of more than 2 square inches.

Atmospheric Transmission in the IIR Region

The absorption of water vapor in the atmosphere is the primary determinant of the wavelength bands in which IIR communication can be carried on. The effects of source distribution, filters, and cell-response cutoffs are subordinate.

Methods of Measurement. The transmission of solar radiation from 0.8 to 7.0 μ through the water vapor in the atmosphere was measured under Contract OEMsr–990 with a Perkin-Elmer infrared spectrometer.[18] Harvard Contract OEMsr–60 [32,33] set up what was essentially a reflecting telescope with a recording bolometer receiver, the telescope being covered by a thin glass prism, for studying the transmitted spectrum from a tungsten lamp source 5,000 yards away across Broad Sound, in the vicinity of Boston. The wavelength range accessible with this apparatus was from 0.4 to 2.7 μ. The transmission of solar radiation as a function of solar altitude (air mass) was also studied carefully.

The quantity of water vapor in the path, reduced to *centimeters of precipitable water* [cm ppt H_2O], was estimated in the first contract from meteorological data and was determined in the second one from wet and dry bulb measurements with a sling psychrometer. A quantity of 1.0 cm ppt H_2O is approximately the amount of water vapor traversed in a 1,000-yard path, at 20 C and 50 per cent relative humidity, which we may tentatively define as "average clear weather" for IIR communication purposes.

Water Vapor Transmission. The results of the two studies are in substantial agreement with each other and with measurements in the literature.[34,35,36] Lambert's law that the same fraction of the radiation is absorbed in each successive element of distance holds very well for the transmission through haze in the NIR but is not even approximately obeyed in the IIR. The rule in the IIR is that the bulk of the absorption in average clear weather takes place in the first half mile, and that the total change thereafter amounts to only a very few per cent for paths up to several miles. This is shown by Table 4 which gives integrated transmission values determined from the spectrograms recorded under Contract OEMsr–60.

Table 4. Fraction of incident energy transmitted by water vapor in near and intermediate infrared regions.

cm ppt H_2O	Region * I	II	III	IV	V
1.1	0.74	0.81	0.71	0.64	0.57
3.6	0.64	0.64	0.51	0.52	0.50
7.5	0.51	0.56	0.44	0.51	0.48

* See Figure 35.

The regions indicated are those marked in Figure 35 (bottom), which shows the transmission of solar radiation as a function of wavelength with about 2.7 cm ppt H_2O in the path, as estimated under Contract OEMsr–990. The integrated transmissions over these regions on Figure 35 agree roughly with those in Table 4, the latter values being much more accurate because more careful determinations of the absolute incident and emergent energy distributions were made. Regions I, II, and III are in the NIR; Regions IV and V in the IIR. For the last two regions, to a good approximation, we may take the loss of signal by atmospheric absorption and scattering to be about 6 db in the first half mile and zero thereafter in average clear weather.

Reason for Departure from Lambert's Law. Lambert's law is violated in the IIR because the absorption is not produced by a continuous spectrum but by a large number of very sharp and intense lines the natural widths of which are much narrower than the distances between them. The centers of the lines are completely absorbed by the water vapor in paths of just a few feet, and the radiation passed comes through many narrow gaps between adjacent lines. Theoretically, for lines of equal intensity and spacing, the fraction absorbed is the ratio of the effective line width to the gap width. This fraction grows at the rate at which the relative line width grows, that is, approximately, only *as the square root* of the path length for transmission values between about 0.1 and 0.9 μ.[34,35] Where the lines are of equal spacing the absorption increases more slowly. Actually, in the IIR, with the relevant transmissions integrated over both strong absorption bands

and almost transparent regions, after the first great decrease the transmission changes very slowly indeed.

Haze Losses. Those working under Contract OEMsr-60 found the losses from scattering by haze to be negligible at 2.5 μ. At shorter wavelengths the losses increase strongly with decreasing wavelength, becoming as great as 20 db at 0.68 μ for the 5,000-yard path length in weather which was still clear enough for making spectrograms.

Transmission through Chemical Smokes. These results are confirmed by tests with smokes. The Bureau of Ordnance cooperated with those working under Contract OEMsr-60 in testing reception through large quantities of various kinds of chemical fogs and smokes in the path over Broad Sound. Smoke which would have made NIR communication completely impossible would have had little effect on IIR communication. For example, a plume of HC (hexachloroethane, zinc and zinc oxide) smoke from a standard smoke pot, which was completely opaque visually to a 1,000-watt searchlight, attenuated the beam on the average more than 20 db at 0.85 μ, but only 4 db at 2.1 μ.[33] The results with other smokes were similar; details may be found in the original report.

Comparison of Atmospheric Transmission in the Near Infrared and Intermediate Infrared. A continuous-spectrum IIR system evidently has a considerable advantage in atmospheric transmission over an NIR system, for which the haze transmission losses increase regularly (Lambert's law) at about 4.5 db per mile in average clear weather. An IIR system could start with an initial handicap, say, of 20 db in overall performance compared to an NIR system. The IIR system would lose only the additional 6 db in the first half mile, while the losses of the NIR would steadily increase. The performance of the systems would become equal at ranges of about six miles in average weather. At longer ranges the IIR system would excel because it would not be nearly so much affected by weather as the NIR system.

It is worthy of note that the water vapor absorption losses in the IIR actually may be less serious even than those in the FIR (8 to 13 μ), which is a region usually considered quite transparent. This is easily understood when it is realized that the gaps between the water vapor bands in the IIR, if expressed in the more fundamental units of *frequency* rather than of wavelength, are actually *wider* than the gap in the FIR between the 6 and 25 μ bands. Also the intensity of the IIR bands is lower than that of the FIR bands. The result, for which there seems to be some experimental evidence, is that the atmosphere should be *more* transparent in the IIR than in the FIR.

Use of Glass or Plastic Optical Elements

Glasses and plastics always have strong absorption bands near 3 μ. The absorption bands of glass are exhibited in the curves of Figure 35 for thin Corning 430 and Nonex samples. It was thought at first that these bands might be serious enough to require the elimination of all such material from the optical path. But since in just a short path the 2.7-μ water vapor band absorbs all the wavelengths in this vicinity anyway, it seems that moderate thicknesses of glass or plastics can be tolerated. [This is true only for the IIR *communication* problem; for *heat detection* with PbS cells it may be essential to eliminate *all* glass and plastics from the path, so as not to diminish in any way the small but important longest-wave tail response to radiation transmitted through Region VI (see Chapter 9).] For communication, probably as much as two centimeters of good optical glass can be used in the path without any serious effect on range. As filters and cover glasses alone may add up to about this thickness, probably mirrors rather than lenses should be used in the IIR optical systems for collimation and focusing. A design like that of type W is better in this respect than any of the other vibrating-mirror designs.

Shift of Long Wavelength Cutoff in Glass Cells. A related problem is that of the effect produced by the difference of the response curves for melted PbS layers in air and thin evaporated layers inside a Nonex cell. The latter type, represented by NU 2126 in Figure 35, can be made more reproducibly, but they have a shorter wavelength cutoff as shown in Figure 35. However, the water vapor absorbs most of the wavelengths in the neighborhood of this long-wave cutoff and the shorter wavelength of the cutoff produces no appreciable loss in communication range. The difference of the response curves is due not only to the absorption of the Nonex but also to the failure of the thin evaporated PbS layer to absorb the longer wavelengths, as shown in the PbS transmission curve at the top of Figure 35.

Filters

Filters for the IIR must transmit very little below 1.4 μ if they are to give security against enemy detection by phototubes, TF cells, and image tubes, and very well in Regions IV and V if they are to give maximum communication range.

Types. Various Corning glass filters in blue and blue-green of the proper thicknesses promise to give adequate differentials in transmission between the NIR and the IIR. Plastic filters, such as the XRF-1 types developed under Contract OEMsr-1085 for this problem may also be satisfactory (see Chapter 2).

Transmission Curves. The infrared transmission curves of the suitable glasses and plastics tested are almost identical. The curve for Corning 430, 2 millimeters thick, is shown in Figure 35B.

The significant differences in the curves of various samples are those which occur in the important region of very low transmission near 1.2 μ and would not show in this figure. Because of the small transmission at this wavelength, it is essential, in measuring transmission curves for comparison of IIR filters, to use a double monochromator in this neighborhood. Scattered background light will cause serious errors with singly dispersing instruments like the commercial infrared spectrometers.

The Corning glasses have some blue and green visual transmission which can be eliminated by the addition of Corning 2540 or 2550. The curve for 2540 in the NIR is also shown in Figure 35. These glasses have negligible absorption in Regions IV and V. They may be made as thick as necessary to limit the NVR to the desired values, without having any great effect on the IIR range.

Holotransmissions for PbS Cells and TF Cells. The best filter tested under Contract OEMsr-990 consisted of 2-millimeter Corning 430 plus 2-millimeter 2540. The holotransmissions of this combination and of 2540 alone are given in Table 5A for TF and PbS cells. The values were measured on the photocell test set (Chapter 3); the source is an unfiltered tungsten lamp at 2848 degrees K, with the light chopped by a sector disk at 90 cycles.

The S/N ratio of a good PbS cell at present is about 20 db less for this source (unfiltered) than for a TF cell of the same size. Taking the TF cell S/N as a reference level, the S/N ratios of the two cells with filters are as shown in Table 5B.

Range computations can be made from these data only after a source is chosen for the IIR work.

TABLE 5. Comparison of NIR and IIR sources, filters, and cells.

Cell	No filter	2540 alone	430 plus 2540
	A. ehT *values* (given as decibel loss)		
TF	0 db	—15 db	—75 db
PbS	0 db	— 5 db	—20 db
	B. *S/N ratio* (relative to value for TF cell with white light, 2848°T_c)		
TF	0 db	—15 db	—75 db
PbS	—20 db	—25 db	—40 db
	C. *S/N ratios for tungsten source at 1500 K* (relative to value for TF cell with white light at 2848° T_c at same source power)		
TF	—15 db	—30 db	—90 db
PbS	—10 db	—15 db	—30 db
	D. *Estimated reception ranges with 1500 K tungsten source* (assuming PbS range of 20 miles with no filter)		
	Vacuum range		
TF	15 miles	6 miles	400 yd
PbS	20 miles	15 miles	6 miles
	Average clear weather range		
TF	4.5 miles	3 miles	400 yd
PbS	14 miles	10 miles	4 miles

Sources

From the transmission curve of Corning 430 plus the water vapor in a long path (Figure 35, shaded area), it is seen that the wavelengths effective in carrying the communication in a secure PbS system are near 1.7 and 2.2 μ. An efficient IIR source must radiate a large fraction of its energy in these regions and must be suitable for modulation.

Gas Discharge. Xenon and krypton (or other rare gas) sources like those used in the Touvet system and the V-M system may be capable of emitting electrically modulated radiation in these regions under certain excitation conditions (see "Source," Section 4.5.3). Very little is known about this possibility.

Mechanical Modulation. A source which would certainly work is a tungsten lamp with its radiation mechanically modulated by a vibrating mirror as in the type G and type W systems.

For greatest efficiency with such a source, the lamp temperature should be adjusted to about 1500 K, so that the maximum of the radiation curve will be near 2 μ. An input power of, say, 100 watts at

this temperature would require a source several millimeters in diameter. This is large but not prohibitive for a vibrating-mirror system. A feasible beam width in this case would be 1 or 2 degrees or larger. With increase of temperature from this value, the beam solid angle decreases faster than the efficiency, so that the effective IIR holocandlepower and the range are both greater at the higher temperature for the same source power. This is probably the reason for the use of tungsten lamps near 3000 K in the German Lichtsprecher, even with PbS cell receivers.

A rough calculation shows that the output from a 1500 K source in Regions IV and V would be about 10 db more than from a source of the same power at a temperature near 3000 K, while the output near 1.0 μ would be about 15 db less. These may be taken to be roughly the differences produced in PbS and TF cell responses, respectively, if a 1,500-degree source were substituted for the source in the photocell test set.

Range and Security

A PbS-cell tungsten-lamp IIR system with suitable filters would be simpler to make than an NIR system. The small PbS cells now made are well adapted for use in a narrow beam system which has its own kind of security. One or more of the devices considered for increasing the security of the NIR system could also be added later to an IIR system if needed.

The range and security of the PbS-cell tungsten-lamp system can be calculated with the help of certain assumptions.

Detection by TF-Cell Receiver. The range of *detection* of the source with a TF-cell receiver can be estimated by comparing the range of TF-cell reception with that of PbS-cell communication reception. Applying the above corrections for source temperature to the relative S/N values given in Table 5B, we then have for a source at 1500 K the values given in Table 5C. Assume that an IIR system with PbS cell and 1,500-degree tungsten source can be constructed which has a vacuum range of 20 miles with no filter. Then, on the assumption that PbS and TF cells of the same size are interchangeable in the receiver, the communication ranges can be computed from Table 5C and are given in Table 5D. In average clear weather, with the 430 plus 2540 filter combination, the IIR communication range is 4 miles, the NIR range 400 yards. The very approximate nature of these estimates must be emphasized.

To give the range at which it could be *detected* that a modulated infrared source was operating, the range of 400 yards, which refers to TF cell for voice *reception,* should probably be doubled. Enemy use of very large receiver areas of two or three feet in diameter would give ranges several times larger still, perhaps up to a mile or more. This is of course the maximum NIR detection range in the center of a beam 1 or 2 degrees wide.

A more dense filter than the 430 used in this calculation would give lower TF cell ranges, with little effect on PbS ranges. Of course, the thinnest filter that could be permitted should be used in order to keep the PbS ranges as great as possible.

Detection by Phototube Receivers and Electron Telescopes. Phototube receivers and electron telescopes give detection ranges comparable with those of TF cell receivers for NIR sources. An IIR filter, however, affects their response to an IIR source much more than it affects the response of a TF cell, because of the longer wavelength threshold of the latter. The differential factor is estimated to be of the order of 10, when Cs-Ag-O S_1-type photoemissive surfaces are considered. With such a factor, the detection ranges with these devices should be only about one-third of the ranges obtained with TF-cell receivers.

Visual Range. The visual range of an IIR system may be reduced to as small a value as desired by use of sufficient thicknesses of 2540 filter, with little effect on the IIR range.

Intermediate Infrared Communication Range. The vacuum range assumed to be feasible for purposes of computation, for the PbS system in Table 5D, is not excessive as can be seen by changing this system over to an NIR system and comparing it with known NIR systems. If the tungsten source used in computing the table were replaced by one of the same power at 2848 K with the same beam width, the TF-cell vacuum range of the imagined system with the 2540 filter would become about 14 miles. Such a range is not much greater than that expected for type W with a 3-degree beam, and it is considerably less than that expected for type G with a 100-watt source, a Corning 2540 filter, and a beam width between 1 degree and 4 degrees. The latter, if converted to IIR, should therefore give a larger range than the system imagined in Table 5D.

Because of the low attenuation, an increase of source power (or beam intensity) in the IIR is much more effective in increasing the range than in the NIR. A factor of two in source power in the NIR produces a change of about 15 per cent in the range of an NIR system whose ACW range is about 5 miles; in the IIR, the change produced would be about 40 per cent.

Possible Interference. The possibility of an IIR voice system encountering serious interference from low-temperature engine exhausts in the field of view has already been mentioned. Only operational tests can determine the importance of such interference. Filtering out the strong low-frequency components of such noises in the receiver amplifier might give adequate relief.

4.9 SUMMARY OF RECOMMENDATIONS

If development of infrared communication systems is to be continued, some particular and general recommendations can be made. The particular ones concern continuation of the work in progress at the termination of World War II:

System	Recommendation
Type W	Further tests
Type E	None; system in manufacture
P-G	Further tests
P-P	Completion and tests
V-M	None; no features not duplicated in other systems
Touvet	Study of source Elimination of a-f modulation Improvement of receiver angles
Photoelastic shutter	No further development; tests of Navy pilot models
Spectral modulation	Construction and study

Further general recommendations can be made on fields of interest and promise which deserve study by the Armed Services for possible future military applications. It is assumed that the Services will keep abreast of source, filter, photocell, and circuit developments. It is to be hoped that careful study will be given to each of these various systems by other branches of the Services than those for which they were developed. The following problems should be undertaken:

1. Application of intelligibility-band-pass studies [41] to the above systems.
2. Increased security: modification of above systems for greater security and construction of new ones from this point of view.
3. Adaptation of above systems to perform recognition function (see also Sections 5.2 and 5.6).
4. Direct comparison of weight, stability, and efficiency, etc. of electrically modulated and vibrating-mirror systems designed for the same range, angles, and security.
5. Temperature and altitude effects, and engine exhaust difficulties, with various detector cells.
6. Daylight communication: PbS cells and others.
7. IIR systems: PbS cells and others.
8. NIR (beacon) and IIR (heat radiation) tracking devices: with TF and PbS cells and others.

A great number of these infrared communication devices have now reached, or almost reached, the quantity production stage. But as yet little attention seems to have been paid to the fact that many of them will interfere greatly with each other if they are ever used close together in the field. This situation becomes more serious with the addition of the systems described in Chapter 5. Before further production or development continues, the various branches of the Armed Services should immediately take steps to channel all their infrared efforts through a single agency which could allocate frequencies, wavelengths, and signaling methods to the various devices; otherwise, mutual interference, noise, backscatter, and cross talk may prevent any of these equipments from attaining their ultimate performance in the field. Further remarks on this subject will be found in Section 5.6.

SYMBOLS IN EQUATIONS

(Photometric and holophotometric symbols not distinguished)

For Section 4.1.3

- a total photoresponsive surface area of detector cell
- a' maximum projected photoresponsive area of bare cell
- a_0 total effective luminous surface area of source
- a_0' maximum projected area of bare source
- A receiver entrance pupil
- A_t exit pupil of transmitter
- α hpi transmitter beam width
- B surface brightness of source
- β hpr width of receiver directivity pattern
- d distance between transmitter and receiver axes (in a transceiver head)
- Δf receiver bandwidth
- e_r receiver efficiency (optical)
- e_t transmitter efficiency (optical)
- e_t' product of transmission and reflection coefficients in transmitter system
- E illumination (flux/unit area) on a surface in the transmitter beam
- f focal length of transmitter optical system
- F threshold flux on receiver entrance pupil
- ϕ total emergent d-c flux from bare source
- h ebT of filters in beam
- I maximum practical rms variation of beam candlepower during modulation
- I_0 maximum bare source candlepower
- k, k', k'' constants in range equation, including photocell noise, geometry factors and aberration factors
- O_r receiver optics factor
- O_t transmitter optics factor
- Ω_r hpr solid angle of receiver directivity pattern
- Ω_v hpi solid angle of transmitter beam
- p object distance: from source or transmitter to image-forming, intensity-reducing lens or mirror
- q image distance: from same lens to the image of the source or transmitter
- R distance from transmitter to receiver
- R_T operational range (limit) of communication system in weather with transmission T
- R_v vacuum range of a system (limit)
- T atmospheric transmission (per sea mile)
- z rms variation of intensity relative to mean d-c intensity with modulation device removed

For Section 4.6.2

- A, A', B, B' emergent beams
- α phase angle of time variation of supersonic wave
- β angle by which analyzer must be rotated from crossed position to produce given transmitter intensity with no modulation
- $\Delta\mu$ difference in refractive indices of birefringent
- φ medium
- ϕ'_m optical phase shift (introduced by birefringent medium) between components of light parallel and perpendicular to optic axes
- ϕ_m maximum of θ at an antinode at a given instant
- ψ_m maximum of θ'_m reached during an r-f cycle
- I instantaneous intensity transmitted through crossed Polaroids
- I_0 intensity transmitted through parallel Polaroids (no modulation)
- I_t average of I over one r-f cycle
- J_0 Bessel function of order zero
- p, q Neumann's photoelastic constants
- t time; thickness of glass block
- τ period of supersonic wave
- θ phase angle of supersonic wave as function of position on block

Chapter 5

NEAR INFRARED RECOGNITION AND CODE COMMUNICATION SYSTEMS

By *John R. Platt* [a]

5.1 INTRODUCTION

IN THE PRESENT CHAPTER is collected an assortment of *near infrared* [NIR] systems which are similar in basic principle to the voice and code communication systems of Chapter 4, but which have two fundamental differences. The systems of this chapter all transmit and receive no voice but only low-frequency code signals, from 90 to 600 cycles, and they each perform some function other than that of communication.

The type D and D-2 systems (Section 5.2) began as identification units, that is, the first models were designed with 360-degree transmitters to broadcast national or specific identification call letters over and over, almost continuously in all directions. The function of receivers in such systems is to determine whether an object or target in the field of view has or has not such identification. Although the emphasis in this type D development was later concentrated on rapid code communication, identification was retained as a secondary function.

The *plane-to-plane recognition* [PR] system (Section 5.3) performs only the identification function.

The *retrodirective target locator* [RTL] (Section 5.4) uses infrared radiation to locate certain special mirrors in the field of view; it was designed originally to locate life rafts at sea.

In the *Japanese infrared detection* [JAPIR] system (Section 5.5), the transmitter is omitted and the function of the system is reduced to the detection of enemy infrared sources.

The general remarks on types of systems given in Section 4.1.2, on components and ranges in Section 4.1.3, and on the state of the art at the beginning of the National Defense Research Committee [NDRC] program as given in Section 4.2 may also be applied to the systems to be discussed in this chapter. The four equipments to be described here are rather closely related and are all low-audio-frequency intensity-modulation systems, so that further breakdown into categories like those of Section 4.1.2 is unnecessary (see Table 1 of Chapter 4). Two of the systems employ electrical modulation of a tungsten filament source; the others modulate the beam with a mechanical rotating sector.

The other methods of modulation and methods of obtaining greater security are described in Section 4.1.2, and include polarization or wavelength modulation, which could also be applied to the problem of recognition and identification. Most of these other methods entail an increase in weight and complexity; but one method leading to greater security —the use of the *intermediate infrared* [IIR]—could be introduced immediately, by a simple interchange of filters and photodetector cells.

As many of the voice systems described in Chapter 4 had provision for code communication, it might seem at first glance that the code systems to be described in this chapter are an unnecessary duplication. This is partly true, so far as code communication alone is concerned, but none of the systems of Chapter 4, except possibly the P–P system (Section 4.4.4), have the 360-degree transmitters required to perform the identification function which is performed by the type D, D–2, and PR systems to be described.

The fact that most of these all-around identification systems are designed only for code and not for voice is a result of the general economics of weight, power, and beam angle in signaling systems. As discussed in Section 4.1.3, a wide-angle system is a short-range system. To get militarily useful ranges, considerable source power must be used, 1,000 to 1,300 watts in the type D development, for example. This large essential drain of power puts a premium on simplicity of modulation methods and considerably favors simple electrical or mechanical coding, as compared with voice modulation which involves comparatively large and heavy power amplifiers. To get around this difficulty, it has been

[a] Northwestern University, Evanston, Ill. Now at University of Chicago, Chicago, Ill.

proposed to use 10- to 40-degree directed-beam low-power transmitters which could sweep the horizon continuously with a code signal for identification and could stop for challenging and voice communication. This possibility has apparently not been explored very far. It, together with some other possibilities for amalgamating the identification and voice systems in order to make a great saving of weight and power, needs study from the point of view of all the military requirements, including the total shipboard or aircraft infrared installation. This question will be discussed further in Section 5.2 under "Evaluation" and "Recommendations," and in Section 5.6.

5.1.1 Military Applications

The first important military application of the systems described in this chapter is the equipping of ships and planes with all-around infrared beacons and directed receivers so that the craft are immediately identified as friendly by any other similarly equipped ship or plane within range. The second important application is the use of these same beacons and receivers for challenge and all-around (code) communication after identification has been established. The same principle can, of course, be applied to tanks, infantry units, and front-line trench positions. The advantages of the infrared in security for military situations requiring radio and radar silence have already been described in Section 4.1.2.

Examples of both of these applications are type D and its later and more useful successor, type D–2 (Section 5.2). The complete production model of a D–2 system, for ship-to-ship use, weighs about 1,200 pounds and has eight 170-watt transmitter beacons for 90-cycle code, giving 360-degree horizontal coverage with a 50-degree vertical *half-peak-intensity* [hpi] width. It has two automatically scanning receiving heads with *half-peak-response* [hpr] angles of about 12 degrees. The *average clear weather* [ACW] range (see Section 4.1.3) is not known exactly, but is estimated to be about 6.5 sea miles.

An example of the identification and recognition application without code communication is given by the PR system. One complete aircraft installation weighs about 25 pounds and has four 6-watt tungsten lamps, coded at 90 cycles, one mounted on the top and bottom of each wing tip for all-around (spherical) coverage, and a receiver with a 15-degree hpr angle. Obtainable ACW ranges are expected to be greater than 2,500 yards for every direction of the receiver from the source lamps. The receiver can probably be mounted on gimbals and electrically aligned with the plane's guns so as to give a warning signal if they are trained on a friendly target. The ACW ranges in either direction between the type D system on a ship and the PR system on a plane are expected to be about 12,000 yards.

The all-around source required for identification from all directions gives these systems a somewhat lower security against enemy detection and demands much more power than is needed for a narrow-beam system of the same range. Thus all-around type D requires about 1,300 watts of source power compared to about 100 watts for the 15-degree type E system of about the same range (Section 4.4.2) in spite of the much sharper tuning of the type D code receiver.

The RTL system also performs a kind of identification function but is suited to a different type of military situation. This system has a wide-angle transceiver (4 to 15 degrees) *at one station only*. The other station carries one or more precision retrodirective triple mirrors which reflect the 90-cycle transmitter beam accurately to the receiver. The receiver then gives a signal when a mirror is in the field of view. These mirrors weigh only ¼ pound apiece and could be attached to life jackets for detection during search for survivors at sea, an application of civilian as well as military interest. They could be fixed to buoys or markers for channel location, or carried by landing boats or infantrymen so as to indicate the progress of an attack to a central headquarters station. Ranges up to about 2 miles were obtained with a working model using a 300-watt lamp with an hpi transmitter beam width of about 4 degrees. The transceiver station equipment weighs about 115 pounds. In the case of navigation markers and landing craft where some power is available to drive a rotating 90-cycle sector (coded, if desired) over the triple mirrors, the range can be increased to about 4 miles. Replacing the receiver in the RTL system with an infrared electron telescope for visual detection of the mirrors might give comparable ranges and a much more convenient apparatus. However, the Navy specifically did not want the use of a telescope because of the

required constant attention and consequent operational fatigue. Such a telescope would necessarily add at least one person to a plane crew (the RTL was designed for aircraft installation). Where secrecy is not essential, an unfiltered beam can be used with some increase in range.

The remaining system to be described here, the JAPIR system, has a different function. It was designed to be placed on aircraft for detecting enemy NIR sources within an hpr angle of about 6 degrees; it weighs about 25 pounds. Either steady or modulated NIR beacons may be detected. Code messages from blinker beacons, or from carrier-wave sources modulated at frequencies between 60 and 500 cycles, may be read directly. Voice communication could be monitored if some changes were made in the receiver arrangement. The receiver sensitivity differs by only small factors from the sensitivities of other receivers in the other systems described in Chapter 4 and in this chapter, and consequently the maximum range of detection of enemy systems will probably be similar to the operating ranges of those systems. For high-candlepower transmitters like those discussed here (types D, D–2, E, and Touvet), the maximum ACW range of detection can be computed to be about 9 miles, if the JAPIR system were placed in the exact center of the beam. In actual operational tests of the JAPIR system, a 240-watt NIR-filtered all-around lamp mounted on a target plane was only picked up by the system at ranges of about 3,000 yards in average weather. The JAPIR system will probably not detect intermediate infrared transmitters at distances of more than a few hundred yards.

5.1.2 Systems not Developed by NDRC

The code systems to be described here have something in common with blinker code searchlight or beacon systems adapted to the NIR by a suitable filter, except that such systems are designed for visual observation through an infrared electron telescope. Both the Army and Navy have done extensive work with such systems.

Type P

Code messages may be transmitted by type D or type P, a system developed by the Polaroid Corporation under Navy contract.[b] This system deserves mention here because of the unusual modulation method and the elegant presentation of the message at the receiving end.

The type P transmitter is fed by a standard teletypewriter, which interrupts a steady line current in regular patterns according to the letter struck by the operator. The current "breaks" are converted into pulses operating a flash lamp NIR source, the "makes" into pulses operating a second flash lamp source. The two flash lamp transmitters are covered by complementary polarizing sheets so that at the receiving end the pulses are received alternately by two vacuum phototube units covered by complementary analyzers. The receiver pulses are converted back into "makes" and "breaks" of a steady line current operating a receiving teletypewriter, which automatically types out the message on a tape in the usual way.

With 3,500-watt lamps, the ACW night range is about 6 sea miles with day range about 4 sea miles. Speeds up to 60 words per minute are obtainable. A similar system of lighter weight is being developed under Navy contract by Farnsworth Television and Radio Corporation. This uses only one lamp without polarization, indicating the "makes" with one flash and the "breaks" with a double flash.

5.2 TYPE D SYSTEM

Description and Performance

Course of Development. The type D system, a 90-cycle code system at present adapted for ship-to-ship identification *and* communication, was developed by University of Michigan Contract NDCrc-185 (Project Control NS-151). This development was initiated in October 1942 under the Bureau of Aeronautics [BuAer] primarily for ship-to-*plane* recognition and was taken over after February 1943 by the Bureau of Ships [BuShips], chiefly for ship-to-ship code communication. In explaining the course of this development three stages must be distinguished.

The first stage ran from October 1942 to February 1943 and was concerned with ship-to-plane recognition at distances up to 3 miles. The equipment was tested in the latter month at Norfolk, Virginia. A 500-watt mechanically interrupted NIR beacon placed on a coastal patrol yacht was identified with moderate success from a receiver of 14 degrees hpr width fixed in the nose of a PBY5

[b] Information supplied by courtesy of Section 660E, Bureau of Ships.

amphibian plane flying 5 miles or more away. An official demonstration was given on the night of February 12, 1943, to representatives of BuAer, BuShips, and other Army and Navy officers.[1]

There followed the second stage of development under Project Control NS-151 requested by BuShips, in which new laboratory units were designed with emphasis on four new objectives: (1) transmission of code messages, (2) ship-to-ship recognition, (3) automatically scanning receivers, and (4) indication of the bearing of a distant source. Subsequently commercial Navy contracts were let for the quantity manufacture of the type D system based upon the design of these units. Samples were tested near Solomon's Island, Maryland, in July 1943. Improved laboratory type D units were installed on two destroyers, the USS *Carmick* and the USS *Corry,* and tested near Norfolk, Virginia, on February 7 and 8, 1944.[2,6] The contracts for pilot models and later for quantity production were made with Emerson Radio and Phonograph Company, New York City,[4] for type US/D receivers, and with Crouse-Hinds Company, Syracuse, New York,[5] for type US/D transmitting systems. Contracts were also let with GE, Lynn, Massachusetts, and with RCA, Indianapolis, Indiana, for beacons and receivers, respectively.

The third stage of development followed the February 1944 tests. Greater emphasis was placed on the high-speed communication and break-in function of the equipment. In this stage were constructed laboratory type D-2 units,[3] the production of which was taken up by further Navy contracts. The transmitters at this stage were completely redesigned for electrical modulation from a thyratron power supply, giving crisp, fast signaling, with off periods in which the reply from a distant station can break in. Some changes were also introduced in the receiver. Satisfactory field tests of the laboratory type D-2 system were carried out at the BuShips Test Station at Cape Henlopen, Delaware, in September 1944 and March 1945 between the shore station and the USS *Marnell.* The Emerson receivers were revised in accordance with these new developments with no change in type number. New type numbers were assigned to the other new equipments of this stage as follows: RCA[7] receivers were known as type US/D-1; the transmitting systems were known as type US/D-2 with the power supply from Westinghouse Electric Corporation and the beacons from Portsmouth Navy Yard and the Naval Factory at Sommerworth, Maine.

All the receivers in all three stages can receive from all the transmitters, but only the US/D-2 transmitter and its laboratory type D-2 counterpart permit break-in from a distant station.

Complete systems consisting of the US/D-2 transmitters and revised Emerson US/D receivers were installed on two destroyer escort vessels in May 1945 and tested in the Pacific Theater of Operations. The Navy reported some weeks later that the equipment "gave excellent results and met with wide acceptance."[3]

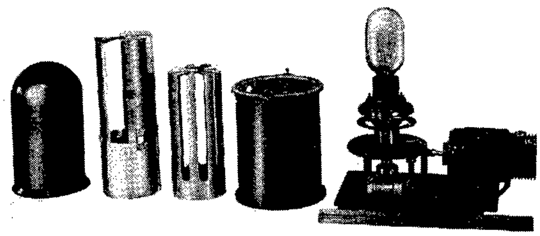


FIGURE 1. Infrared source for ship-to-plane recognition equipment. Left to right: glass cover and filter, coding cylinder, modulating cylinder, cylindrical housing, motor assembly with tungsten lamp.

General Design: Ship-to-Plane Recognition System. The general design of the ship-to-plane system tested and demonstrated at Norfolk in February 1943 is as follows. The 110-volt, 500-watt, T20 tungsten projection lamp (see Section 1.2.2) mounted on the ship is coded at 87 cycles by a nine-bladed cylindrical inner shutter surrounding it, which is driven by a governor-controlled battery-operated 30-volt motor operating at 2,910 rpm (Figure 1). The opaque and transparent sectors of this shutter are equal. An outer shutter rotating at about 40 rpm has three adjustable sectors to provide for transmitting any three-element code letter. The shutters extend well below the lamp, and their tops are cut away, except for a small central disk, so that the source transmits into the whole upper hemisphere except for a small cone of about 20 degrees total angle directly overhead.

The rotating shutters are enclosed in a 5-inch diameter, 9-inch high glass dome the inner surface of which is covered by a Polaroid XR7X25 filter

(see Crapter 2). A motor-driven fan ventilates the dome.

The receiver mounted in the nose of the plane consists of a Cashman thallous sulfide (TF) photoconductive cell with 1-inch square sensitive area (see Chapter 3). This cell is mounted axially at the focus of a parabolic Alzak aluminum reflector, which is 9 inches in diameter and 1.7 inches in focal length, giving an 8-degree hpr angle. The photocell feeds into a fairly conventional two-stage preamplifier which in turn feeds a four-stage narrow-band amplifier peaking at 90 cycles with a 12-cycle bandwidth. The total gain is over 150 db. A sensitivity control is provided. The output can be connected either to a neon indicator lamp or to headphones. When a transmitter comes into range in the field of view the lamp lights, or a code tone is heard.

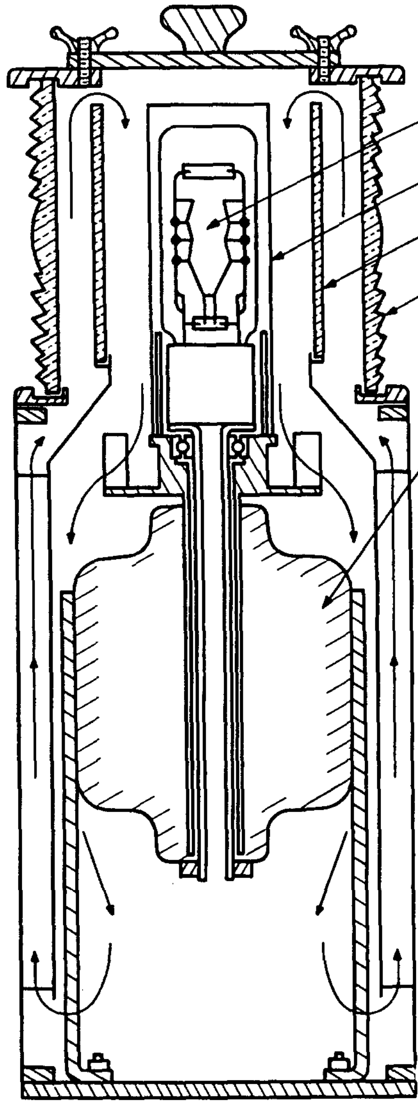


FIGURE 2. Laboratory type D beacons No. 54 and No. 55.

The ship transmitter weighs some 80 pounds, not including the 30-volt battery supply for the modulating motor, and it consumes about 500 watts from the 110-volt line. The plane receiver assembly weighs about 33 pounds including batteries and requires about 15 watts from its own batteries.

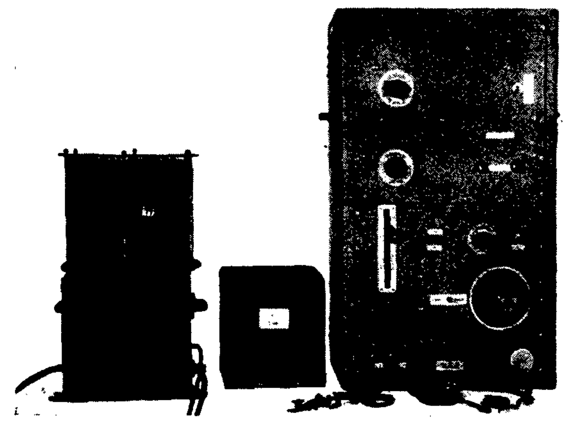


FIGURE 3. Laboratory type D receiver.

General Design: Laboratory Type D. In the second stage of development (ship-to-ship), revisions were made as indicated in Figures 2 and 3. Two transmitter beacons of a design similar to that in Figure 2 were to be placed on each ship so as to cover 360 degrees azimuth without any obstructions by the ship's superstructure. Likewise, two receiver heads like that in Figure 3, one port and one starboard, were intended to be used so they would together scan 360 degrees in azimuth; but in the laboratory type D equipment built up for the USS *Corry*-USS *Cormick* tests in February 1944, only one receiver was actually constructed for each ship.

The 500-watt transmitter lamps used at this stage are nominally of almost 1,000 cycles and were developed especially for this project by the GE Lamp Development Laboratory at Nela Park, Cleveland, Ohio. The inner shutter around the lamp has three sectors and is rotated at 30 rps by a synchronous motor to give a 90-cycle signal. The outer shutter has been dispensed with, and a more flexible (but less crisp) coding is provided by interrupting the

lamp current at the control panel. Any Morse letter may be repeated automatically and continuously, or the operator may send a message with a telegraph key. Either plain glass cylinders or marine Fresnel lenses may be used on the outside of the beacons; the latter confine the beam to about 22 degrees hpi vertical spread, as shown in Figure 4, giving an

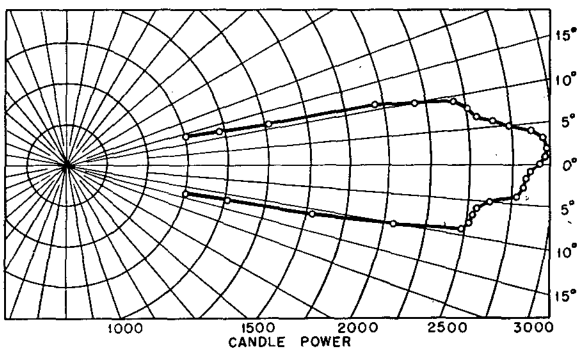


FIGURE 4. Distribution in vertical plane from laboratory type D source in Corning Fresnel lens.

optics factor of about 3×, or about 3,000 horizontal *holocandlepower* (see the Appendix for new nomenclature) when the high-altitude beams of ship-to-plane communication are not needed. A Polaroid filter is placed on the outer cylinder and on an inner glass cylinder such that the combined transmission corresponds to that of XR7X25. The double construction gives a reserve of security in case one layer cracks.

An ingenious synchronization system keeps the sectors of the two beacons on a ship in exact directional coincidence as they rotate so that the two signals are never out of phase.

The laboratory type D receiver, shown in Figure 3, consists of an optical head, training control box, amplifier, and indicator or headphones. The cell and reflector arrangement chosen results in the *directivity pattern* (Section 4.1.3) shown by the dotted curve in Figure 5, with an hpr width of about 11 degrees. The main difference from the earlier model is that each head is now placed on a vertical axle to scan automatically (or manually, from the control panel) back and forth through 290 degrees. The scanning motor is governed by a servomechanism from the training control unit shown in Figure 3, and an indication of the bearing of either the port or the starboard unit at any instant to ±1 degree is provided on the main control unit, also shown in Figure 3. The scanning speed and coder speed can be regulated manually from the latter unit.

The weights of the components of the laboratory type D, exclusive of cable, are:

Main control unit	170 lb
Receiving heads (120 lb each)	240 lb
Training control	40 lb
Sources (85 lb each)	170 lb
Total weight, equipment for one ship	620 lb

The power consumption is 1,000 watts for the beacons (when they are on about half the time), plus some 250 watts for the various motors and the receiver system, all supplied from the 115-volt, 60-cycle ship supply.

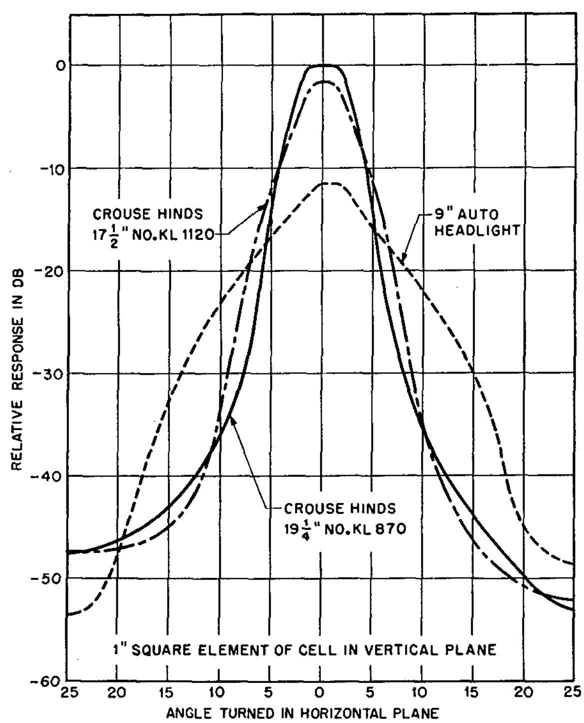


FIGURE 5. Directivity pattern of optical systems considered for type D receiver.

General Design: Laboratory Type D-2. In the final stage of laboratory development, the transmitter and receiver were both adapted for faster coding. The beacons were completely transformed, as shown in Figures 6 and 7. A thyratron supply (Figure 6) provides rectified half-wave pulses from the three-phase 60-cycle ship supply, selecting the pulses to give 90 cycles (see Figure 11). In the final model these pulses energize fifteen 10-watt, 230-volt,

FIGURE 6. Transformer, thyratron control cabinet, and D-2 beacon.

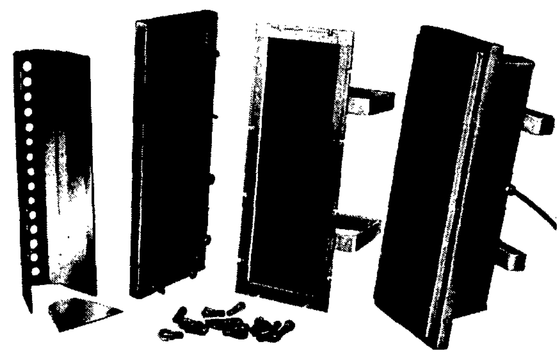


FIGURE 7. Details of D-2 beacon.

10S6 tungsten lamps (Figure 7) in each of eight reflecting troughs mounted in octagon array around the ship's fighting bridge (Figure 8). These lamps cool so rapidly that the backscattered radiation from them does not deaden the local receiver in the intervals between signals as did the earlier 500-watt lamps. The reply from a distant station can be heard, break-in, during these intervals. The faster response of the lamps also makes possible clear coding at speeds up to 40 words per minute which are limited only by the skill of the signalmen, compared to maximum clear speeds of about 10 words per minute with the older design.

The eight beacons give 360-degree azimuth coverage, and the reflecting troughs are designed to give vertical hpi angles of 50 degrees. The mean horizontal intensity without filter is about 1,050 cycles. Corning 2568 glass filters 8 millimeters thick have been used, but Polaroid XRN5PX65 or the Ohio State University [OSU] DR 23u filters

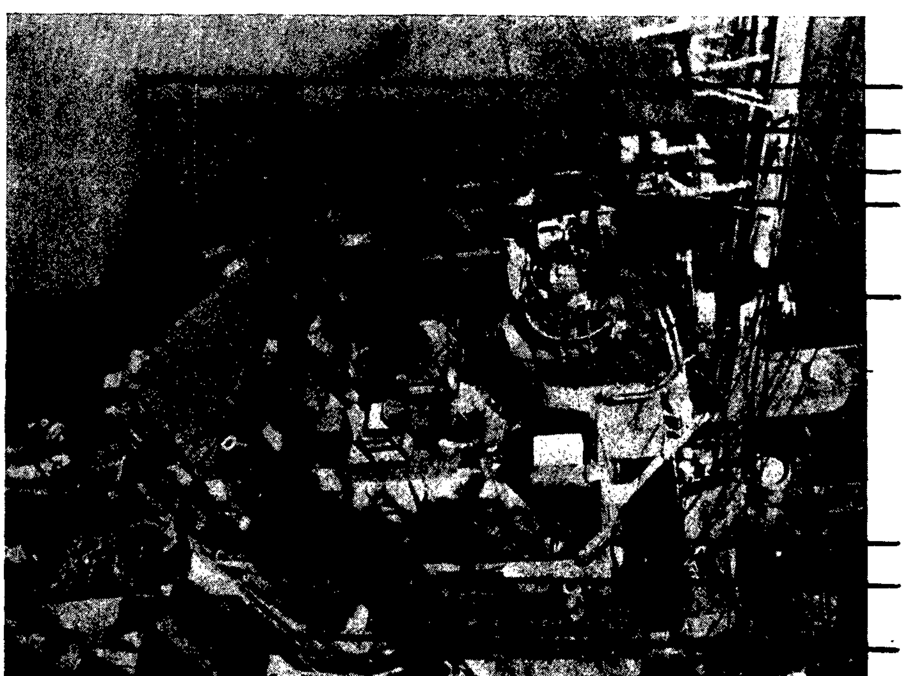


FIGURE 8. D-2 beacons installed. Eight beacons arranged in octagon fashion around fighting bridge.

are preferred because of their higher transmission (Chapter 2), now that they have passed Navy weathering and temperature tests.

In this period of development the receivers, still designed to be two in number on each ship, are gyroscopically stabilized by impulses from the main ship gyro (see Figure 9). The scanning indicator on the control panel (Figure 10) is linked with the ship's compass so that it will give both true and relative bearing of any source in the field of view. The analyzer stage of the receiver-amplifier has been changed so that it also serves as a voltage limiter and prevents the building up of the excessive voltages on the neon indicator lamp (from strong local backscatter) which had delayed lamp extinction on the earlier model and so would have prevented break-in reception even if the transmitter time lag had not been present. This voltage limiting feature actually permits narrowing of the pass band to 9 cycles while still permitting much faster coding speed.

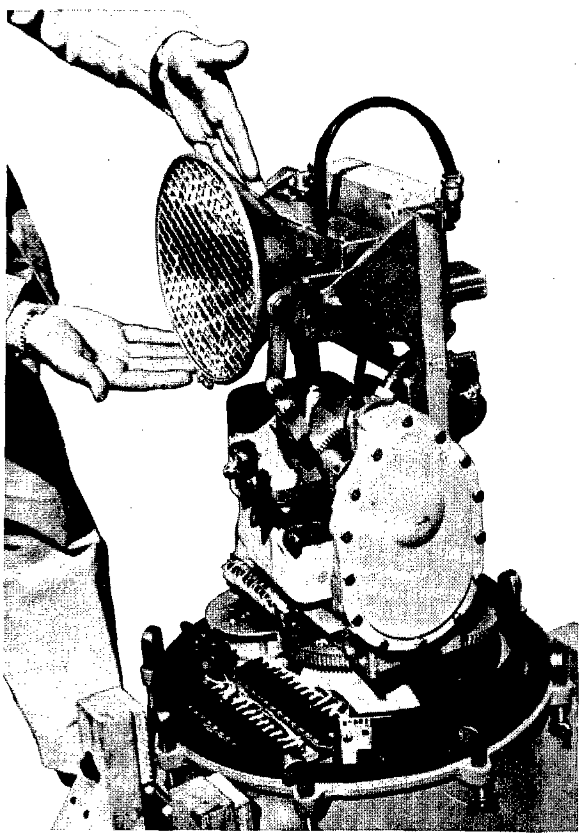


FIGURE 9. Type D-2 receiver head, cover off.

With the break-in system a distant station is detected when the neon indicator lamp gives signals which do not follow the local automatically coded source. After detection of a distant station, communication may be started by a "call-up" program in which the operator holds down his key continuously for several seconds. The neon lamp at the distant station then glows continuously for long intervals while the receiver is scanning in the general direction of the calling ship.

At this stage of development a loudspeaker was added to the headphones and indicator lamp as a device for observing the signal.

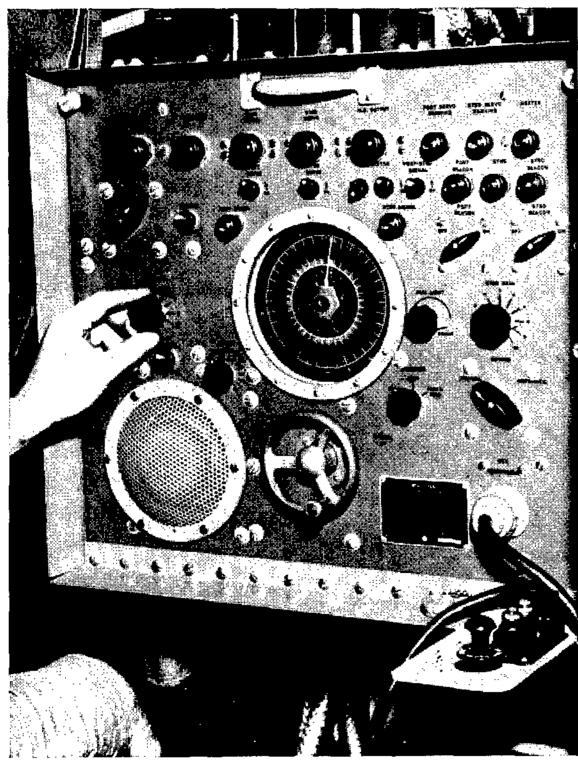


FIGURE 10. Type D-2 main control unit (Emerson).

The weight of a complete laboratory model D-2 ship installation is approximately as follows, exclusive of cable:

Eight transmitter beacons	160 lb
Two receiver heads, stabilizers, and training units	350 lb
Control panel	170 lb
Total for one ship	680 lb

The power consumption is about 1,400 watts for the beacons (when they are on) from the 115-volt 60-cycle three-phase ship supply, plus perhaps 250 watts for the remainder of the equipment.

General Production Designs. The latest US/D-1 receiver and US/D-2 transmitter designs follow quite faithfully the final revised laboratory model, the principal changes being to make the equipment rugged enough to pass Navy shock, vibration, temperature, and weathering tests. The Emerson US/D control panel is shown in Figure 10, and the D-2 beacons shown in Figure 8 are also units available in the open market. The power consumption is, of course, about the same as for the laboratory model, but the weights and sizes are as follows (exclusive of cable):

Unit	Size	Total weight
Eight transmitter beacons	Each 8x8x24 in.	300 lb
Two receivers	Each 20x20x40 in.	480 lb
Servoamplifier	12x20x24 in.	95 lb
Motor generator	8x12x20 in.	125 lb
Control panel	18x24x28 in.	195 lb
Total for one ship		1,195 lb

Security. The desired *night visual range* [NVR] (see Section 4.1.3) of the assembled beacons on one ship was not to exceed 1,200 feet. The filters mentioned above, which were used and recommended for the laboratory type D-2 model, give an NVR, from laboratory measurements, of 500 to 800 feet.

The ACW range of detection of the assembled D-2 beacons on one ship by a type C_3 or type C_4 infrared electron telescope (see Section 4.1.3) is estimated from observations made during field tests to be not over 6 miles. The code message of the transmitters described above can, of course, be read with such a telescope at shorter ranges so that there is not even "message security" (see Section 4.1.2). At the request of BuShips, a modification of the transmitter was devised which gives message security. In this modification, instead of on-off keying, frequency-shift coding was tested, with the frequency changed by the key from a normal 180-cycle tone, to which the receiver is not sensitive, to the 90-cycle tone, to which it is. Arrangements are made to keep the average intensity the same at the two frequencies so that the change is imperceptible in an image tube. Unfortunately the pickup from backscatter when the transmitter is on continuously in this way is so large as to make break-in operation impossible. Whether shielding of the receiver from the local transmitter and backscattering objects can be devised so as to eliminate this difficulty is not known. There seems to be some radio broadcasting as a result of the thyratron pulses in the revised R-2 transmitters, but the seriousness and possible detection range of this is not known.

Range. Although extensive field tests have been made on the type D equipment in various stages of development, only one test seems to have been accompanied by the measurements or estimates of atmospheric transmission which are necessary to standardize the observed ranges (Section 4.1.3). This measurement[6a] gives for the equipment of the second stage a range in vacuum of 20 sea miles with the Fresnel beacon, which would mean an ACW range of about 5 sea miles. The consensus of results with the type D-2 beacons indicates a vacuum communication range of about 30 sea miles. The ACW *communication* range is then about 6.5 sea miles; the ACW range for *recognition* may be about ½ mile greater. The ACW ranges would be increased nearly 1 mile by changing from glass filters to the plastic filters recommended.

Evaluation. The final type D-2 design appears to fulfill very satisfactorily the specifications originally set down for it. However, the D-2 beacons are two or three times as large and heavy as necessary to give the desired beam pattern.

A comparison with the type E ship-to-ship voice communication system (Section 4.4.2) is interesting and instructive because the two developments ran parallel in many ways, and because after February 1943 the communication function was emphasized for type D more than the identification function. For both systems, the final commercial installations built to Navy specifications weigh about 1,000 pounds, a little more for type D, less for type E. Type D has a 360-degree transmitter, 11-degree automatic receiver; type E has a manually operated 12-degree transmitter and 18-degree receiver. Type D ACW code range is about 6.5 sea miles; type E ACW voice range 6.5 sea miles, type E code range 9 sea miles. Infrared telescope ranges are about 9 miles for type E, perhaps 6 miles for type D-2, but type D-2 with break-in feature has no message security against telescope detection. Type D-2 consumes about 1,700 watts on, 250 off; type E consumes 1,100. Differences in range and power are the result of difference in transmitter angles and frequency bandwidth, as discussed in Section 4.1.3. Thus type E as a *communication* device has the obvious advantages of voice communication over code and has greater range (code) and more secu-

rity than type D. The price of these advantages is the comparatively narrow angle of the transmitter, which makes it impossible, without some transmitter scanning system, for type E to be used at all for the *identification* function to which type D is very well adapted.

Military urgency and production pressure, following the successful demonstrations of the early type D models, may have prevented adequate consideration of variant methods and may have led to premature fixing of certain design features, so that it is not known at all whether the present type D–2 models represent optimum design for a system of this type. For example, in the first stage of development the frequency was chosen near 90 cycles for the excellent reasons that it was mechanically convenient and was not too close to the 60- and 120-cycle hum frequencies. Also this frequency was high enough to permit reasonable coding speed yet low enough to avoid the loss in sensitivity then mistakenly thought to exist "because of the dropping response of TF cells at higher frequencies." This 90-cycle frequency was preserved throughout the development so that all models would be interchangeable. It may not be an undesirable frequency now, if the question were looked into, but the original reasons for its adoption have almost disappeared since the system is now electrically modulated and the TF cell threshold sensitivity is now known to extend almost unchanged to at least 3,000 cycles.

Against the 90-cycle frequency is the fact that the received code tone has so low a pitch as to make long attention unpleasant and tiring. To meet this problem two frequency-changers were finally designed, one by Contract NDCrc–185 and one by Emerson Radio, to bring the pitch up near 1,000 cycles as an aid to the operator. Another possible objection to the low frequency is the interference from atmospheric "twinkle" effects (Section 4.1.3), which, it has been suggested, may be more serious here than at higher voice frequencies. Receiver design also appears to be more troublesome than at higher frequencies.

From the point of view of simplicity of power supply, there are good reasons for choosing 60 or 120 cycles for the code frequency.

As a result of the military urgency there also seems to have been no time for adequate consideration of cesium lamp sources at the time that the type D–2 electrically modulated beacon was being developed, although the tungsten lamps in this beacon appear to have a modulation ratio at 90 cycles of the order of 30 per cent, while the cesium lamps have ratios near 100 per cent up to nearly 10,000 cycles.

Now that more leisurely and fundamental programs are again possible it would seem that the whole question of the best frequency for a code system of this type should be restudied carefully, as has been suggested by those working under Contract NDCrc–185.[3] In such a review particular attention should be paid to gaseous discharge sources.

There was another unfortunate result of the military pressure. The parallel development of type D and type E, which was required because of the emergency, resulted in two commercial equipments of great weight and power consumption, the functions of which overlap a great deal but not enough to warrant eliminating either in a military situation requiring the NIR. Also, though they supplement each other, there may be difficulties in using them simultaneously on the same ship because of backscatter and crosstalk. From this point of view it is fortunate that type D has such a low frequency in that the two frequency channels may be sharply separated by wave filters. Even so, the d-c component of backscatter will remain, causing great mutual losses in receiver sensitivity. If the type D frequency were raised, it would go no higher than about 400 cycles before the problem of crosstalk would become very serious indeed.

As the coming of peace provides a breathing spell in which to reconsider the fundamental military needs, serious thought should be given to this whole problem of overlapping—and interference—of functions between recognition and voice communication systems. Considerable attention should be given to the possibility of amalgamating type D and type E into a single system which would preserve the best features and the most important functions of each, and effect a great saving in power and weight. More specific comments will be made below under "Recommendations."

Regardless of these unresolved questions, type D has proved very successful in operation and has received enthusiastic recognition of its military value from Naval officers and from operating personnel.

TRANSMITTER

Beacon Synchronizing Systems. The lamp sources and mechanical chopper designs used during the first two stages of development need no further description here except to mention that the troublesome problem of motor lubrication at the high temperatures (up to 115 C) encountered in the beacon housing was successfully overcome.

However, the use of two beacons on a single ship, in the second stage of development, introduced an interesting complication, namely the problem of developing a synchronizing system to keep the two rotating sectors parallel at all times. The 90-cycle modulation required that three-bladed shutters run in directional coincidence on separate four-pole motors.

The mechanism devised by workers at the University of Michigan under Contract NDCrc–185 to accomplish this involved having both motors rise on starting to full speed unsynchronized. Differential impulses from commutators on the two motors were used to actuate an auxiliary relay circuit. Then if the two motors were out of phase, the current through one motor was weakened by the relay until it "slipped" into directional coincidence with the other motor, at which time the relay ceased to operate. The Crouse-Hinds Company substituted two-pole alternators on the motor shafts for the commutators.

Coaxial Shutter. One interesting variant method of mechanical coding which was explored under Contract NDCrc–185 was the *coaxial shutter.* This shutter consisted of two ordinary three-bladed cylindrical shutters around the lamp, mounted one outside the other on a common axle and both rotated by the modulating motor at 30 rps. If the outer blades are aligned with the inner ones, the light comes through the three gaps and is chopped at 90 cycles; a rotation of the outer shutter by 60 degrees closes the gaps and cuts off the light. Normally, a spring holds the outer one closed; keying applies a brake which drags on the outer one and opens it.

Having a short time lag with such a system means having a small moment of inertia for the outer cylinder and using a stiff spring with a correspondingly high drag in the brake. With the motor used, this drag was sufficient to drop the frequency to 83 cycles when the brake was applied, which is an intolerably large change; a stronger motor would be needed for successful operation.

The reverse system of using the brake to close the shutter and the spring to open it would also be feasible. Braking may be accomplished either by a mechanical brake band or by eddy currents induced by an electromagnet.

Such a device, if perfected, would allow break-in communication with rugged-filament lamps like the original type D beacons, since the coding would not be accomplished by interrupting the lamp current.

Fresnel Lenses and Filters. The candlepower distribution from the special 500-watt monoplane filament lamps used in the first and second stages of development follows approximately the sine law, being greatest (almost 1,000 candlepower) in the horizontal plane and least in the vertical direction. The external clamps and supports for the beacons are designed to give minimum interference with the radiation, but nevertheless cause some weakening of the intensity in certain directions. The beacon shown in Figure 2 has its vertical beams obstructed by the opaque cap, since it was to be used only for transmitting to other ships. The lamp is mounted on a support rod through the hollow motor shaft so that if ship-to-plane communication were desired, the cap could be simply replaced by a filter glass giving a minimum of overhead obstruction.

The filters used were Polaroid XR7X25 or the equivalent and gave an *effective holotransmission* [ehT] (see Chapter 2) of about 0.30 with the TF cells used in the receiver.

Each beacon was supplied with two interchangeable glass housings, either a large plain cylinder to give the sine-law distribution noted above, or a Corning marine Fresnel lens, type 53048–218J. This altered the vertical candlepower distribution as shown in Figure 4, giving an optics factor of 3× by cutting down the vertical spread of the beam to an hpi width of 22 degrees. The horizontal distribution with the Fresnel lens remains equal in all directions, except for losses due to obstructions as mentioned.

Control Panel. The control panel used in the second stage of development contained a special pilot light to show whether the beacons were properly synchronized. It also provided either for sending a message by manual keying or for repeating automatically one or more code letters over and

over. A motor-driven bank of cams which could make contact with a microswitch provided a choice of this automatic signal from among all the Morse letters. The frequency of the automatic coding, in letters per minute, could also be varied.

The increased emphasis on the communication function in the third stage of development made some of these features unnecessary, as can be seen in Figure 10 showing one of the later control panels.

Electrically Modulated Sources. The incandescence and nigrescence times of the large tungsten filament of the lamp used in the first two stages of development are a considerable fraction of a second. Thus even with slow coding at speeds under 10 words per minute (about 1 letter per second) the radiation from the source is fairly strong throughout the off periods and swamps any faint signal from a distant source attempting to be heard. Also an attempt to code at much faster speeds results in fuzzy and confusing signals.

These difficulties were remedied in the third stage of development of the type D–2 system by replacing the one large lamp in each beacon with 120 high-voltage (230 volts), 6-watt (6S6), and later 10-watt (10S6) tungsten lamps. These lamps have fine filaments which will go on and off very quickly. They are mounted in eight beacons for 360-degree azimuthal coverage. Oscillograms of the radiation from these lamps showed that clear coding was possible at speeds up to 40 words per minute. This was confirmed by actual tests at speeds up to 30 words per minute which is about the limit reading speed for most code operators. Since the lamps are on only intermittently, they can be and are operated at about 13 per cent power overload without any serious loss of operating life.

Possible 90-cycle Power Supplies. The 90-cycle mechanical chopper arrangement, while workable with the large beacons, involved troublesome features of synchronization and mechanical maintenance which had already led to consideration of possible electrical modulation. For modulating the many small lamps, the devising of an efficient and trouble-free mechanical chopper would have been very awkward indeed, and electrical modulation became essential.

Two possible systems for 90-cycle-per-second electrical modulation were considered but were not used. One consisted of a generator properly geared to a synchronous motor; procurement difficulties interfered with this arrangement. The second method involved the mechanical selection of alternate pulses from a three-phase 60-cycle Y system. In such a Y system the time between successive maxima is $1/180$ second, and between alternate maxima is $1/90$ second. The pulses could be selected by a suitable commutator and brush arrangement driven by a synchronous motor, but the problems of synchronization and phasing, adjustment of output power, and provision for keying promised to be difficult.

Thyratron Power Supply. The system finally chosen involves a beautiful arrangement for electrical selection of pulses from such a Y system. The basic circuit consists of a set of transformers run from the three-phase supply, with the secondaries connected in a Y. Three thyratrons have their plates connected to the points of the Y and their cathodes connected together. The load is connected between the cathodes and the center point of the Y.

The thyratron grids are normally negative, but are all made positive at the peak of alternate maxima by pulses from a 90-cycle oscillator. As Figure 11 shows, only one thyratron will then conduct, as the plates of the other two are negative for a short time before and after the peak. The resulting pulses through the beacons are shown in curve *F* of Figure 11. The sharp current rise and the long off period during each cycle were found to give a much better 90-cycle light signal from the beacons than was obtained if they were simply run on sine-wave current, with the same mean power input in each case.

The relaxation oscillator was synchronized by 180-cycle pulses from a set of small phase-controlled thyratrons connected in a manner similar to the main power thyratrons.

The bias on the power thyratrons is normally about 200 volts negative, and keying is accomplished by raising the bias to about 60 volts negative so the pulses from the oscillator will initiate conduction in the power thyratrons.

The system is very stable with respect to line voltage changes. The output power can be adjusted for different input voltages and different loads by adjusting the phase of the oscillator pulses and so giving conduction in the power tubes for a longer or shorter fraction of a cycle. In the small thyratrons the phase is varied either by adjusting the phase of a lagging a-c voltage on the grid or by

adjusting the potential of the shield grid. With the latter method, one voltage divider, connected to all three shield grids, will control the three phases together. The correct power setting is shown to the operator by a monitor lamp on the control panel which should be neither brighter nor dimmer than a reference lamp located beside it. Correct thyratron operation is indicated by the 30-cycle flickering of each tube or of a small neon lamp in parallel.

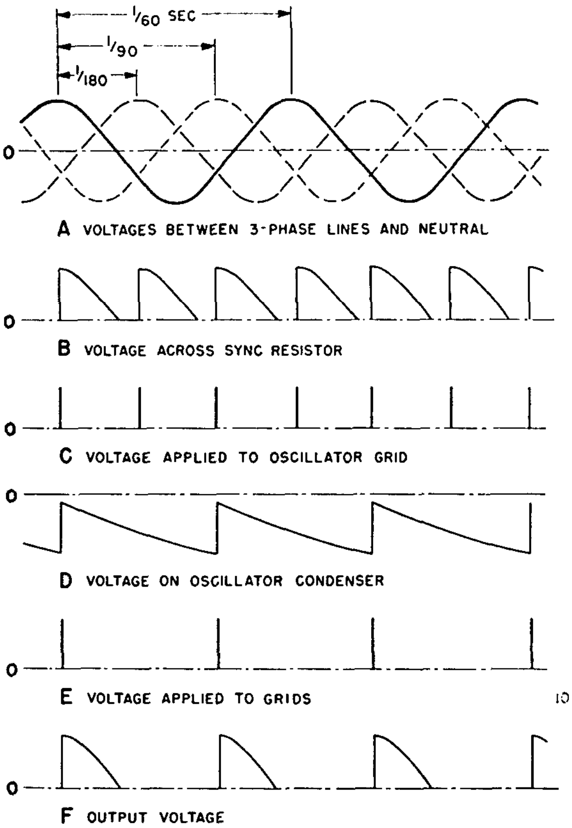


FIGURE 11. Voltages versus time in 90-cycle thyratron power supply, not to same scale.

During installation of the D–2 transmitters for the tests in the Pacific, it was discovered that operation of the power supply interfered considerably with radio communication. The Westinghouse-built power supply was redesigned with filters to eliminate most of this interference, at least on regular Navy radio-frequency bands. Further shielding of output and input lines and grounding of the cabinet may be necessary to make the system completely secure against enemy radio detection and reception.

Inrush Keyers. At the request of Section 660E–9 of BuShips, Contract NDCrc–185 made a study of methods for reducing the time lag of incandescence in large tungsten lamps used for code signaling, including the early type D beacon and others, such as the X2A used by the Navy. Nothing can be done about the cooling or nigrescence time of the filaments, but the heating or incandescence time can be shortened by overvolting the filament for an instant and reducing the voltage to normal as the current approaches normal.

Two devices were built to accomplish this. One is the *saturable core reactor keyer*. In this the 500-watt beacon is placed in series with the two a-c windings of the saturable core reactor. The reactance is large and little current flows until d-c current is made to flow in the third winding of the reactor. A d-c current of 1 ampere controls 10 amperes a-c current. The initial overvolting of the beacon is accomplished by placing a 60-watt tungsten lamp in the keying circuit, which thereby passes a 10-fold greater current when the lamp is cold than after it warms up. Suitable resistors and condensers in the d-c circuit control the time duration of the overvoltage and prevent oscillation.

The second device is the *thyratron-controlled inrush keyer*. In this system, the lamp current is phase-controlled by a thyratron full-wave rectifier of fairly conventional design. Closing the key, which is in the shield grid circuit, permits large current to flow, but starts a condenser charging which slowly changes the grid voltage. This permits conduction later and later in each cycle and reduces the power until the condenser is fully charged.

The condenser discharges at about the same rate as it charges, which is presumably adjusted to the rate of lamp heating and cooling. Consequently, if the key is pressed before the beacon has cooled down, the overvolting is more gentle than when the beacon is cold. Otherwise, there might be danger of burning out the beacon by a series of quick starts with inadequate cooling in between. Probably the saturable reactor keyer has the same desirable behavior because of the similar time lag of its control lamp and condenser in cooling down.

A field test was made on both of these devices at the BuShips test station at Cape Henlopen on July 31 and August 1, 1945. A beacon was keyed by these devices and by a direct keyer. The accuracy of reception was then compared for random code letter groups sent at various speeds and with the beacon at various distances from the receiver. These

devices gave a significant improvement in reception over the direct keyer, but there was some question as to whether the improvement would justify the added weight and cost. The true improvement possible with these keyers may have been underestimated in these tests because of receiver limitations but exact data on this point are not available.

The thyratron keyer would probably be the more flexible of the two systems for general use.

Frequency Shift Coding. Because of the ease of reception of type D messages by image tubes at ranges comparable to the code range of the system, Contract NDCrc-185 considered other methods of operation which might give more message security. The most promising of these was a system in which the type D-2 beacons were normally operated continuously at 180 cycles, a frequency to which the receiver is insensitive; the frequency would then be changed by keying, which would give a signal in the receiver as a code tone in the usual way. This system was especially simple with the thyratron power supply because it involved only the insertion of a 15,000-ohm resistor in the cathode line of the synchronizing thyratrons to produce a 100- to 150-volt synchronizing pulse instead of the former 20-volt pulse and thus drive the relaxation oscillator at the frequency of 180 cycles. Keying closes a relay which shorts out this additional resistor, and the oscillator frequency drops back to 90 cycles. The beacon power at 90 cycles is adjusted by phase control, at 180 cycles by control of the shield grid voltage. The power at the two frequencies can be brought to equality, so that keying produces negligible flicker in an image tube and the signal can no longer be read.

This system was tested on August 14, 1945, at Cape Henlopen and gave ranges similar to those obtained by on-off keying of the beacons. However, the d-c component of the continuous backscatter from a transmitter was so strong as to make a nearby receiver insensitive to weak signals from a distant station at all times. As the preservation of the break-in feature was regarded by the Navy as more important than message security, this method of operation was therefore not adopted in the commercial equipments. Whether greater separation of the transmitter and receiver units on one ship and more optical shielding of them from each other and from backscattering objects would make break-in operation possible with this system is not known.

Reflector Design. In the third stage of development it was desired that the transmitter beam have a vertical spread of 30 degrees above and below the horizon, so that communication would be fairly independent of the roll of a ship. This distribution was achieved by placing a row of 15 of the small lamps in a line in an Alzak aluminum trough as shown in Figure 7. The trough is made of seven plane strips, each of which reflects the light generally into the desired field. The horizontal distribution from a single trough unit follows roughly a cosine law, and

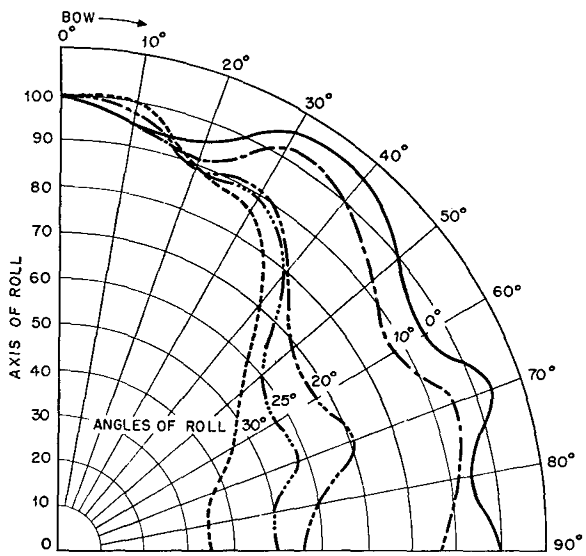


FIGURE 12. Distribution of intensity of US/D-2 beacon for various angles of roll. Expressed in percentages of intensity dead ahead on even keel.

at least four such units are necessary for uniform 360-degree coverage. Eight units were used in the actual type D-2 ship installations. The mean horizontal candlepower of this array, with the usual 13 per cent overload on the small lamps, is about 1,050, and the signal is thus somewhat stronger than that of the type D beacons in a plain housing. This distribution in the horizontal (geographic) plane for various angles of roll of a ship is shown in Figure 12.

This trough design is two to three times larger than necessary for obtaining this distribution and candlepower. A saving in weight of 100 to 200 pounds in the commercial US/D-2 installation could be achieved by a slight redesign of the units.

Filters. The filters used in the first two stages of development were the Polaroid XR7X25 plastic sheets which had ehT values of about 0.30 for the

TF cell receiver and which gave an NVR of the order of 50 feet or less for the two 3,000-hcp Fresnel beacons of stage 2.

In stage 3, Corning 2568 filters were used for actual installations as they were at first the only ones which would pass Navy weathering tests. In 8.5-mm thickness, they give an NVR for a complete type D–2 ship installation (eight beacons in octagon array) of about 400 feet, and an chT for the TF cell of about 0.30. With 7.4-mm thickness, the NVR approaches 1,200 feet, chT 0.32. Now that Polaroid PVA filters and Ohio State University [OSU] filters have passed the weathering tests, they are recommended for use on the type D–2 beacons. With thicknesses and dye concentrations giving an NVR near the limit of 1,200 feet desired for type D–2, these filters have TF-cell chT values between 0.55 and 0.60, which corresponds to an increase in ACW communication range of the equipment of almost 1 mile over the range obtainable with the Corning filters.

Receiver

Cell Arrangement. The photodetectors used throughout the type D development have been the Cashman TF cells with about ¾x¾-inch sensitive grid area (type A cells). Indeed, these cells were designed and constructed by Northwestern University under Contract OEMsr–235 almost entirely to meet the specifications and requirements of the type D development (Section 3.3.1). Various cell and mirror arrangements have been tried but the one actually adopted in all stages of development has been the mounting of the cell with its grid horizontal at the focus of a 9-inch diameter, 1.7-inch focal length parabolic Alzak aluminum reflector (an auto headlight mirror), as shown in Figures 3 and 9. With the present type A cell design, the cell is mounted parallel to the axis of the mirror, with its base in a socket at the vertex of the mirror. The horizontal directivity pattern (Section 4.1.3) from this arrangement is shown in Figure 5; the vertical pattern is similar. The hpr width is about 11 degrees.

The directivity patterns for the same cell in some larger mirrors are also shown in Figure 5. As expected from the discussion in Section 4.1.3, the use of the larger mirror area increases the sensitivity, but decreases the hpr angle of view; or, to say it another way, the response with the larger mirrors (about 18-inch diameter) is better throughout the central 10-degree cone, worse outside.

In spite of considerable changes in the main function and manner of use of the whole system, the cell and mirror arrangement has been kept almost fixed throughout the development; this was done partly in order to facilitate production. If this work is to be carried farther, as now seems likely, one of the first points to be reconsidered might be whether the cell and mirror arrangement is still the best for the present purpose of the system. Gyrostabilization has eliminated the need of the large vertical angle, if only ship-to-ship communication is intended; a narrower horizontal angle of view might be better. The acceptance of narrower angles in both dimensions would greatly increase the attainable sensitivity and range (see Section 4.1.3). In particular, two TF cells of sizes quite different from the present type D size are now available. With the present mirror, use of the present ¼x¼-inch cell (see Chapter 3) would give about 1.5 miles more ACW range than the type A cells, and would give hpr angles of 4 degrees. Use of the 1¼x2-inch (type B) cell would give about 0.3 miles less ACW range than type A cells, but would give hpr angles of about 25 degrees. With the proper 18-inch diameter mirror, all these ranges would be increased about 1.5 miles, hpr angles cut in half.

Mechanical Operation. The receiver heads are driven by reversing motors for automatic scanning or for manual scanning in a fairly conventional manner. In the second stage of development the scanning speed could be adjusted at the control panel, but this feature was later eliminated as being unnecessary. Microswitches limit the travel of each head and reverse the scanning motor. The motor may be stopped and, by means of a selsyn arrangement, the beacon may be pointed manually in any direction by the operator at the control panel. A selsyn operated by the orientation of the heads can be used to drive the bearing indicator on the control panel so that it gives a continuous indication to the operator of the direction in which either the port or starboard receiver is pointing, as desired. The accuracy of these selsyns and the sharpness of the central peak in the receiver directivity pattern is such that bearing of a distant station can be obtained to within 1 degree of arc. In the final model signals from the ship's gyrocompass were sent to a second bearing card within the bearing

indicator so as to give true bearing as well as relative bearing (Figure 10).

The receiver heads in the first type D equipment were mounted on a vertical axle which swung with the roll of the ship (Figure 3), but in the final model, type D–2, impulses from the ship's gyrostabilizer drive a motor which keeps the axis of rotation accurately vertical and the receiver pointed accurately at the horizon (Figure 9).

Preamplifier. In the first phase of development, a conventional two-stage preamplifier was used, having a gain of 48 db. Later the first stage of the preamplifier was made a cathode-follower stage just as in the TF-cell preamplifiers used in the type E development (Section 4.4.2). In the second stage of development, one of the two tuned circuits used was incorporated in the preamplifier, but this was removed again in the last phase of development. The preamplifier box of the laboratory type D is seen in Figure 3; in type D–2 the preamplifier itself is mounted behind the receiver head, as seen in Figure 10.

Amplifier. In the airplane receiver used in the first stage of development the main amplifier had two tuned and two untuned stages. Several variants were later produced, including a power amplifier designed especially for operating headphones above aircraft noise levels.

All have as their function the amplification of the received code tone to the point where it will operate either a neon indicator lamp on the control panel or a pair of headphones, or a loudspeaker.

The narrow band-pass, about 10 cycles wide, peaking at 90 cycles, at first was obtained by two single-frequency resistor-capacitator analyzer circuits tuned to slightly different frequencies, 87 cycles and 93 cycles. Each circuit worked into a negative-feedback amplifier stage. In the type D–2 system the use of the overload limiter made it possible to narrow the frequency band somewhat, eliminating one of the tuned circuits.

The amplification was controlled at first by a step attenuator on the grid of the first tube in the amplifier, because it was feared that a continuously variable potentiometer of the usual type would be noisy on aircraft or on shipboard. Later a suitable potentiometer was found for this control.

A rectifier-filter unit supplies 115 volts d-c for all filaments so that the receivers can be run from either alternating or direct current.

Output Limiter. The bandwidth of about 10 cycles was adequate for a code speed of about 8 words per minute, as used in the first type D beacons. This bandwidth, in the conventional linear circuits used at first, gave the receiver signal a rise and decay time lag of the order of $\frac{1}{15}$ second. Figure 13 shows the receiver time lag in an oscillogram of the response to the letter F sharply coded at 5.5 words per minute. This lag was not objectionable, as it was no greater than the time lag in the filaments of the 500-watt beacons. Indeed, with the receiver at maximum sensitivity, it would continue to pick up backscattered radiation from nearby beacons for a period of several seconds after they were turned off. But when the change was made to the final small-filament, short time-lag, type D–2 beacons to permit break-in operation, it was also necessary to reduce the time lag of the receivers to correspond.

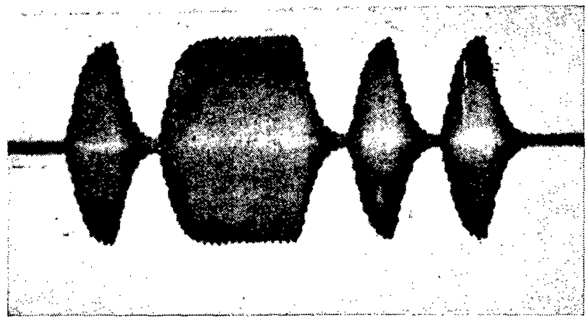


FIGURE 13. Oscillogram of type D receiver response to the letter F, sharply coded at 5.5 words per minute.

As the attainable speed of the new transmitter was of the order of 40 words per minute (greater speeds are useless because of the human limitations of the operator) the new receiver speed had to be comparable. Such speeds, with Morse letters, require time lags of the order of $\frac{1}{40}$ second or less, and the receiver band-pass would conventionally have to be about 40 cycles or more wide to achieve such a fast response. Such a width would have greatly increased the noise voltage over that obtained with the 10-cycle bandwidth, and thereby greatly reduced sensitivity.

This impasse was ingeniously surmounted. A voltage-limiter stage was introduced in the receiver before the analyzer stage so that the voltage level could never rise more than 2 db above the value necessary to light the neon lamp. Thus the voltage

had only to rise 2 db above threshold to give maximum lamp signal, and had only to fall 2 db from maximum in order to extinguish the lamp. Since the usual response time is reckoned as the time for voltage to change by about 9 db, the neon lamp is lighted or extinguished in an interval equal to about one-fourth of the response time. With the 10-cycle bandwidth, which has a response time of the order of $\frac{1}{10}$ second, a time lag of $\frac{1}{40}$ second for the neon lamp is achieved using the limiter system. Thus the desired increase in code reception speed by a factor of 4 is obtained with no increase in bandwidth or loss in sensitivity. Actually a slight narrowing of bandwidth was introduced in the final receivers without any serious effect. The output of the limiter is made linear up to and slightly beyond the point where the neon lamp is excited, so that the threshold sensitivity of the receiver is unaffected. The limiter introduces distortion of the output which is noticeable in headphones but does not interfere with the intelligibility of the received signals.

Control Panel: Presentation. Control panels at the type D and type D–2 stages of development are shown in Figures 3 and 10. The signal neon light is shown in Figure 3 in the upper right-hand corner. In the equipment shown in Figure 10, the port and starboard indicator lamps are on each side of and just above the bearing indicator dial. The handle for manual scanning is below the bearing indicator.

In operation, the gain control is normally set so that when the local beacon is off occasional noise pulses light the neon lamp, but not enough to confuse such a response with a distant signal. The coding on the local transmitter will then in general be repeated faithfully by the lamp until the receiver scans across a distant source. Then the code pattern will be altered or the neon lamp will glow continuously until the receiver has scanned across the source. The general location of the distant source is determined by observation of the bearing indicator at the part of the scanning cycle where these irregular signals occur. Call-up and communication may then proceed as described previously under "General Design: Laboratory Model Type D–2."

The headphones are about 10 db more sensitive and give ACW ranges about 1.5 miles greater than the neon lamp. For threshold signals the headphones operate best with the lamp turned off.

The use of a call bell or horn to give an audible indication of the presence of an incoming signal is highly desirable and would release the operator for other work. With such a bell, arrangements would have to be made to deaden the receiver during the instants that the local transmitter is on, so that backscatter would not produce calls. For maximum sensitivity, occasional false "noise" signals on the bell would have to be tolerated, but these would probably be less tolerable than the false flashes on the neon lamp and thus there might be a loss in sensitivity of about 10 db from that of the neon lamp presentation, corresponding to a further loss in ACW range of about 1.5 miles.

Signal Frequency Changers. Although there is no loss in range occasioned by the poor tone quality of the 90-cycle signal in the receiver, operators accustomed to radio reception object to this quality. One method of increasing the frequency to give a more pleasing pitch would be to connect the neon indicator lamp as a relaxation oscillator and amplify the resulting signal for headphones or loudspeaker. Another method is used in the Emerson radio-frequency changer which has a continuously operating 1,000-cycle oscillator connected to the headphones through a "trigger" tube by the receiver 90-cycle signal.

It may be noted here that some experiments were made under Contract NDCrc–185 on a receiver for unmodulated NIR radiation, which operated by transforming such radiation into a 300-cycle code signal, but the results did not appear to be promising for shipboard use. (However, the JAPIR aircraft system in Section 5.5 can perform this function.)

Test Beacons. Two different kinds of microflux sources or microbeacons for testing the operation of receivers were developed under Contract NDCrc–185 during the type D development. They have already been described in Section 4.1.3, as they are usable with all types of NIR receiving systems.

Operational Tests

Ship-to-Plane. Identification of a ship by a plane was tested with the equipment in the first stage of development on the nights of February 9 and 10, 1943, and was demonstrated to representatives of BuAer, BuShips, and other Army and Navy officers on February 12, 1943, at Norfolk, Virginia, with the cooperation of the Navy and Naval Air Force.[1] The 500-watt beacon (Figure 1) was installed above

the wheelhouse of the coastal patrol yacht PYC26. The receiver head (14 degrees hpr width) was fixed pointing straight ahead in the bombardier's compartment in the nose of a PBY5 amphibian plane.

On February 9 the PYC26, anchored near the mouth of Chesapeake Bay, and the PBY5 made several straight runs from various directions heading toward the ship. The source on the ship was operated continuously and the coded signals were picked up at distances of about 3.5 miles. On February 10, with the ship anchored near Cape Charles in a spot with less traffic and fewer shore lights, detection was obtained at distances estimated as up to 5 miles. No attempt was made to determine maximum range.

February 12, the night of the official demonstration, was relatively clear. One flight was spoiled because of blocking of the beam by the ship's smokestack owing to a poor choice of flight direction. On the other flights, ranges estimated at over 5 miles were obtained. The pilot was able to use the apparatus as the sole means of locating the ship, and it appeared that he could have kept his bearing on the ship solely by observation of the indicator lamp.

No difficulty was experienced from vibration, but the amplifier used was not powerful enough to give a signal in the headphones over the plane noise. Later a power amplifier was constructed for this purpose.

It was found that 60-cycle shore lights also gave signals in the receiver.

Following these tests the equipment was turned over to BuShips for field tests during which a range of over 4 miles was obtained on a land station.

Solomon's Island Tests. Under Project Control NS-151 BuShips then requested the construction of six automatic receivers and two modulated transmitters. The improved and modified models of this second stage of development were tested between ships near Solomon's Island, Maryland, early in July 1943. Ranges up to 9 miles were attained on a night of better than average visibility.

In these tests the receiver was mounted on a tripod and could be rotated at 2, 4, 6, and 10 rpm. Coding speeds were variable from 5 to 15 words per minute. A scanning speed of 5 rpm and coding speed of 10 words per minute appeared to be best.

These tests were so successful that BuShips requested construction of two more complete sets, each with two transmitters and one receiver, rugged enough for shipboard installation and tests under simulated operating conditions.

USS Carmick and Corry Tests. At the end of the second stage of development, the beacons, receivers, and control panels were as shown in Figures 2 and 3. This equipment was tested on two destroyers, the USS *Carmick* and the USS *Corry,* about 40 miles off the coast near Norfolk, Virginia, on the nights of February 7 and 8, 1944.[2,3] One ship could call the other, then the automatic scanner on the receiving ship could be stopped and messages exchanged by code. The relative bearing of a transmitting ship could be obtained correctly to within about 2 degrees.

The two beacons, port and starboard, on each ship gave a total of 360 degrees coverage. The single receiver on each ship scanned only 270 degrees.

Receiver vibrations interfered with determination of maximum range on the first night. On the second night, a very clear night with bright full moon and calm sea, ranges up to 6.5 sea miles were obtained with plain beacons, up to 13 miles with the Fresnel lenses.

Code speeds of about 10 words per minute were felt to be the best. Receiver threshold angles of view were determined by various ranges; values decreasing from 24 to 12 degrees were obtained, with range increasing from 3 to 7 miles.

On the second day daytime signaling was attempted with no success even at ranges as short as 1,000 yards.

There was some interference of one beacon with the TBS radio. A 21-inch NIR searchlight was easily detected by the receiver at 2 miles. The officers and personnel reacted favorably to the equipment, noting especially that little special training was needed to operate it. There was no objection to the bulk or weight, but the development of break-in operation was highly recommended. More powerful lamps and larger reflectors were suggested for increasing the range. A true bearing indication was recommended.

The success of these tests led to Navy orders being placed (with manufacturers) for ten transmitters, each having two beacons and one control panel and automatic keyer; and for ten receivers, each having two heads, one control panel, and one servoamplifier—all to be suitable for permanent ship installation.

Cape Henlopen Tests. The first field tests on the laboratory model type D–2 system, as designed for break-in operation, were made at Cape Henlopen on September 5 and 6, 1944. The fine-filament sources and the receivers were operated at 60 cycles to simplify the tests of the feasibility of the new design. Communication was carried out between the USS *Marnell* and the shore station. The tests were only qualitative in nature but proved satisfactory, and work was immediately started on a more rugged model of the beacon and on the development of the 90-cycle thyratron power supply.

Further field tests were made at Cape Henlopen with the final laboratory type D–2 systems on March 19, 20, and 21, 1945, again between the USS *Marnell* and the shore station. Signaling speeds of 30 words per minute were recorded, the speed being limited by the skill of the operator rather than by the performance of the equipment. Break-in operation was satisfactory even at threshold ranges.

No attempt was made in these tests to determine maximum operating ranges, but readable signals were received at distances up to 6 sea miles.

Pacific Tests. The latest type D–2 equipments were installed by BuShips aboard two destroyer escort vessels in May 1945 for tests in the Pacific Theater of Operations. The tests were started early in June 1945 and continued for several weeks, with the general report being made by the Navy that the equipment "gave excellent results and met with wide acceptance."

Other Tests. Some other field tests on related apparatus have been mentioned above under "Inrush Keyers" and "Frequency Shift Coding."

Present Status

The equipment and facilities and part of the personnel of Contract NDCrc–185 at the University of Michigan have been transferred to a Navy contract with the same institution to continue this and related work. Quantity production contracts have been placed by the Navy with several manufacturers for both type D and D–2 systems.

Recommendations

The time seems ripe for reconsideration of a number of type D features, from the point of view of type D operation alone.

First, the low 90-cycle frequency may be a disadvantage, now that the practical factors in its initial adoption have been modified by later developments. Work has already been started by BuShips on higher frequency identification sources, such as high-power cesium lamps. Other gas discharge tubes should also be studied, also methods for coding them efficiently and for obtaining message security. Those working under Contract NDCrc–185 have also recommended study of 60-cycle and 120-cycle beacons because of the saving in weight on a power supply for them.

Second, the present US/D–2 beacon design is larger and heavier than it needs to be, as mentioned above under "Reflector Design." Some thought was given to reducing its size and weight during the development, but a great improvement still seems possible.

Third, the present receiver directivity patterns may no longer be especially well suited to their function, and a change in cell size or mirror size or both may be in order. Those working under contract NDCrc–185 propose saving weight by using a wide-angle receiver without the gyrostabilizer.

Fourth, the use of lead sulfide (PbS) cells (Chapter 3) for reception in the IIR must now be considered as offering a new identification channel.

Further recommendations must be made if type D is to be operated in the presence of other NIR systems.

If the Pacific tests did not include tests on the mutual operation of and interference between type D and other shipboard infrared devices, such tests should be carried out in the near future. Systematic studies of this kind were recommended in a BuShips report [6b] as far back as March 1944. If they have actually been made, no report has been received of them.

Since work on both type D and type E systems is being continued by the Navy, it is most important that designs, functions, and call-up and communication procedures be jointly and immediately reconsidered as a basis for revising them to reduce the mutual interference if installed on the same ship, or, better, amalgamating them into a single system as suggested above under "Evaluation."

If interference between type D and type E on the same ship is to be avoided, the following rules must be followed. First, the type D code frequency must be well out of the critical voice band from 1,000 to 2,000 cycles if the voice receiver and code transmitter are to be operable simultaneously, or

vice versa. Type D must stay below 400 cycles or go above 3,000 cycles if the present type E is to function at all on the same ship. Second, even with frequency separation, the d-c part of the backscatter will reduce the sensitivity of both receivers unless transmission and reception are sharply separated further either (1) in *time,* as by a send-receive switch, (2) in *space,* as by accurate directional beaming and shielding of receivers, or (3) in *wavelength,* as by use of the NIR for one function and the IIR for the other, or (4) in some combination of all these ways.

As for amalgamation of the two systems, several things have to be considered—their functions, necessary beam and view angles, the methods of communication, and perhaps new experimental operating data on backscatter—before detailed recommendations can be made. It may not be feasible to have the same source beacons for both voice and all-round code because of power and modulation requirements. If this is so, an amalgamation might still be made of the receiving heads and of the control panels, with a possible saving of several hundred pounds for a single shipboard installation over the combined weight of both systems. A narrow-beam voice system with compact optical head like the RCA type G (see Section 4.3.1) would coalesce very easily indeed with the stabilized type D receiver.

5.3 PLANE-TO-PLANE RECOGNITION [PR] SYSTEM

Description and Performance

Course of Development. In June 1944, Section 16.4 of NDRC proposed to several different branches of the Armed Services the development of an NIR plane-to-plane identification system similar to type D (Section 5.2) but lighter in weight. BuAer took up this proposal and as a result Project Control NA–194 was assigned to those working under Contract NDCrc–185 to develop type D. The specifications were for the development of all-round (spherical) transmitters and for receivers with fore-and-aft coverage and some directional indication. The ACW range was to be over 2,000 yards, NVR less than 100 feet, weight less than 25 pounds, power less than 240 watts. For plane-to-ship identification, which was also wanted, the ACW range to and from type D was to be 12,000 yards. Presentation of the signal in a gunsight, as a warning against firing on friendly planes or ships, was desired.

Not all these requirements were accepted by Section 16.4 or met in the unit developed (the *PR system*).[9] Studies were made with direction-indicating receivers. The receiver adopted for the first model is simply a stationary forward-pointing unit (for fighter planes) similar to that of type D with an hpr angle of view of 15 degrees.

This development was carried out under Project Control AC–101, requested by the Army Air Forces, in addition to Project Control NA–194, since AC–101 requested the development of an identification system with essentially similar objectives.

Three complete sets of the equipment, ready for installation in airplanes, were shipped in July 1945 to the Patuxent River Naval Air Station for operational tests which had not yet been carried out in January 1946.

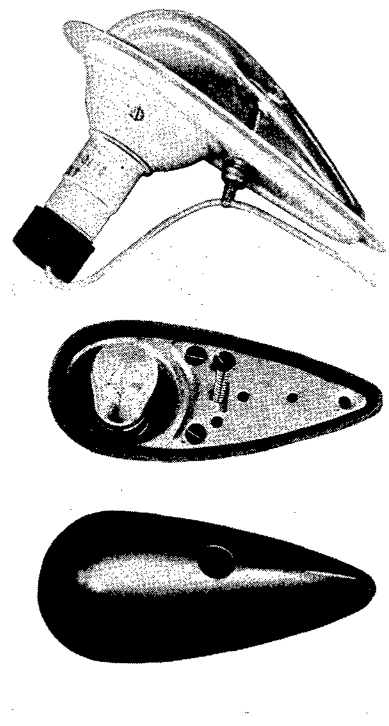


Figure 14. Nacelle beacon (PR system).

General Design. The sources on each plane are four 6-watt, 115-volt type 6S6 tungsten lamps mounted one above and one below each wing tip in small nacelles of NIR filter glass as shown in Figure 14. At least one lamp can be seen from every

direction. The lamps are operated from the plane 115-volt, 800-cycle supply, interrupted by a 90-cycle commutator and a mechanical coding disk (Figure 15) which repeats a single call letter about 25 times per minute.

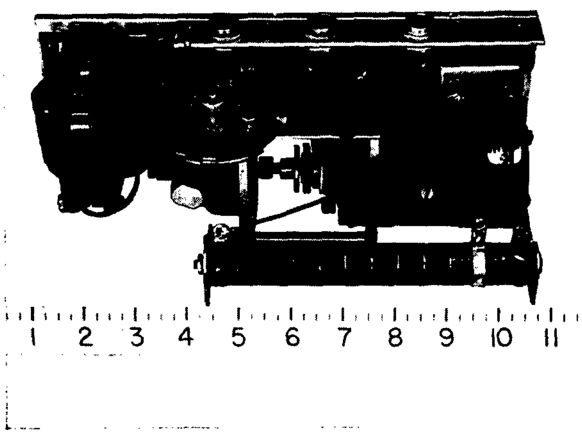


FIGURE 15. Interior of PR modulator-coder unit.

The receiver consists of a type A TF cell mounted axially in an 8½-inch diameter, 1¼-inch focal length Alzak aluminum reflector, as shown disassembled in Figure 16. This gives an hpr width

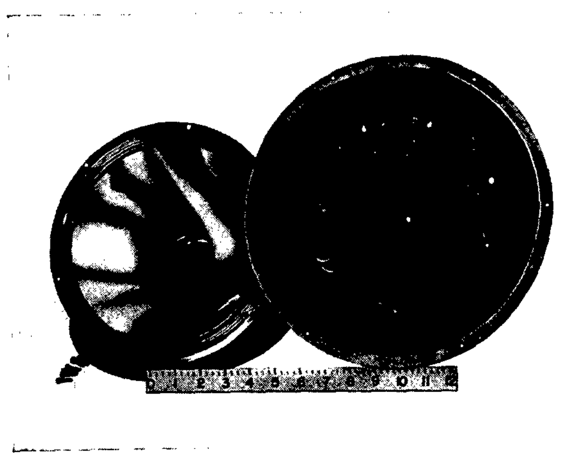


FIGURE 16. PR preamplifier with reflector removed.

of 15 degrees. The cell feeds into a cathode follower and one stage of amplification in the preamplifier mounted directly behind the mirror. The signal is then carried over a shielded cable to the amplifier, which introduces another stage of amplification before applying the signal to a neon indicator lamp mounted in a Polaroid dimming socket on the instrument panel of the airplane. The frequency response curve peaks at 90 cycles with a width of about 6 cycles.

The total weight of the equipment is about 25 pounds. It requires about 35 watts of power from the 800-cycle, 115-volt a-c aircraft supply (most of which is consumed by the transmitter lamps) plus about 53 watts from the 28-volt d-c supply.

Security. The Corning glass nacelle filters are approximately equivalent to 2.4 mm of Corning 2540 filter and give an NVR less than the 100 feet specified.

The ACW range to a type C_3 or C_4 infrared electron telescope is estimated from experience with type D and type E to be about 3,000 yards.

Range. The vacuum range computed from laboratory measurements is 4,000 yards in a direction from the plane in which only one of the sources is visible; the ACW range is then 2,800 yards. For directions in which two or more sources are visible, the range is correspondingly increased, becoming about 3,500 yards ACW for two sources, for example.

Evaluation. The system fills the major requirements specified in Project Control NA-194 except for the request for some directional indication. It was the conclusion of those working under Contract NDCrc-185 that this could not be obtained without a great increase in complexity and weight and a loss in range. It is considered that the receiver could be mounted on gimbals (in a patrol bomber) so as to be electrically pointed with the guns and give a gunsight indication of a received signal, provided the necessary additional weight could be tolerated.

The possibility of scanning a field for directional indication was eliminated because of the great time lag of TF cells and consequent slow scanning required. It was recommended that PbS cells be studied in this connection, as the latter have short time constants. Of course, the tungsten lamps could not be efficiently modulated at the higher frequencies required for fast scanning and would have to be replaced by, say, some modification of the experimentally developed 20-watt cesium lamps (see "Recommendations," Section 4.4.2) which give 200 per cent light modulation efficiency (see Table 2 of Chapter 4) up to 5,000 cycles. It would seem

that the question of scanning and directional indication with a PR system should be considered further in connection with the other Navy specifications on the equipment.

It might be pointed out that the ranges predicted here are of the same order as those expected at night for the *voice* plane-to-plane communication (P–P) system discussed in Section 4.4.4, although the very wide-angle reception of the latter—120 degrees fore and aft, with the receivers used—reduces sensitivity so that much more power (500 watts) and weight (100 pounds) are required. One question might be whether the P–P and PR systems could not, for many purposes, be combined in a single system which would perform both functions.

Transmitter

Sources. Because of thermal lag in the filaments, the modulation at 90 cycles is not complete. The signal strength of one of the 6-watt lamps is equivalent to that of a 4-candlepower tungsten lamp with its beam chopped by a rotating sector to give a square-wave pattern.

The 90-cycle coding commutator is on the shaft of a governor-controlled 2,700-rpm 28-volt d-c motor (Figure 15). The coding disk is run from the same motor through a reducing gear.

Receiver

Preamplifier. The preamplifier is mounted immediately behind the receiver mirror, as shown in Figure 16. An interesting feature is the use of another TF cell of matched resistance as the load resistor for the actual receiving cell. This keeps the resistances balanced for the low temperature encountered at high altitudes where the cell resistance may rise as high as 100 megohms as compared with about 10 megohms for room temperature. The use of a reactance load has been proposed in the P–P system to meet this problem of the change in resistance, whether with temperature or with background light (see "Preamplifier" under Section 4.4.4).

The cathode-follower stage does not amplify the signal but does amplify the microphonics due to plane vibration. The use of a thermostatically controlled heater for the cathode-follower tube has been considered for reducing the noise from this source (see also "Preamplifier" under Section 5.5 for other methods of eliminating vibration noise).

After the cathode-follower stage, the amplification stage feeds into a low-impedance output stage to permit transmission over a shielded cable to the amplifier.

Amplifier. The amplifier contains a gain control, an analyzer stage, and a final output stage.

The power supply for the TF-cell and amplifier plate voltage on two of the units constructed consists of a full-wave transformer-rectifier and filtering circuit run from the 800-cycle 115-volt supply. On the third unit constructed, a voltage-doubling circuit is used without any transformer.

The threshold of the equipment is limited entirely by the TF-cell noise which is considerably greater than the noise produced by the amplifier used.

Backscatter. Since, for identification purposes, the lamps and receiver must all be operated continuously, backscatter from the local coded sources may seriously limit the sensitivity to distant sources. Night tests were made during a light haze with receiver and sources in relative positions resembling those expected in a plane installation. A reduction of sensitivity of about 8 db was required to suppress the local signal on the indicator lamp when two sources were used, 25 feet to one side of, and about 5 feet behind, the receiver. It was hoped that use of shields around the receiver to limit the field of view and around the sources to keep radiation out of the field for a distance of several hundred yards in front of the plane would eliminate this difficulty.

Positional Indication. At the request of BuAer, a receiver optical system was designed and constructed under Section 16.5 by Contract OEMsr-1219 at the University of Rochester, which sent radiation to one of four TF cells according to the position of the source—above or below or to right or left—of the axis of view. This system had an $f/0.56$ objective made of Plexiglas elements and a specially designed mount of four optical bars to split the field into quadrants and to conduct the light to the four cells. The response in each quadrant extended out to about 12 degrees from the axis.

However, the best sensitivity with this device was 14 db below that of the one-cell (type A) receiver described above, and was only 5 db above the response of a bare type B TF cell without any optical system. It was concluded that the value of the quadrant indication was not worth this sacrifice in sensitivity.

Test Beacon. A test beacon constructed for check-

ing the operation of the PR receiver in the field has already been described in Section 4.1.3.

Operational Tests

No operational tests have been recorded except those mentioned previously under "Backscatter."

Present Status

Three preliminary models are awaiting operational flight tests at Patuxent River Naval Air Station.

Recommendations

The operational tests, when carried out, will probably lead to some recommendations on the present units.

In addition, it would seem important to use such equipment as this in investigating the aircraft scanning problem and the problem of electrical alignment with the guns, as mentioned previously under "Evaluation." In particular, the use of a higher code frequency, perhaps up to 3,000 cycles, should be studied (with sources such as the cesium lamp with suitable TF-cell or PbS-cell amplifiers) in the interest of increasing feasible scanning speeds.

5.4 RETRODIRECTIVE TARGET LOCATOR [RTL]

Description and Performance

Course of Development. At the request of BuAer, a project was inaugurated in September 1943 by the University of Michigan under Contract NDCrc-185 to construct an airborne transceiver for sending out a visible or NIR beam and detecting its reflection from life rafts equipped with Mt. Wilson precision glass retrodirective triple mirrors.[10] The orders of magnitude of attainable ranges, both from air-to-sea and from land-to-land stations, under various conditions were to be determined with a simple working model for the purpose of guiding further development plans. Over-water tests of the model were carried out at the Patuxent River Naval Air Station in December 1943 with the cooperation of BuAer.

General Design. The RTL system requires a transceiver at one station and one or more triple mirrors at the other. The general design of the RTL transceiver is shown in Figures 17 and 18. Because of the highly accurate retrodirective property of the Mt. Wilson triple mirrors—the deviation of the reflected beam being held by the manufacturing tolerances to less than 5 seconds of arc—it is essential that source and detector be as closely adjacent as possible. To achieve this a small source is mounted directly in front of the central area of a large receiver aperture.

The source consists of a 300-watt, 30-volt, T–10 projection lamp with C–13 filament (see Section 1.2.1), backed by a spherical mirror of 3-inch aperture placed at the focus of a Fresnel-type optical signal lens of 5⅜-inch diameter and 3½-inch focal length. This arrangement provides a beam with hpi width about 4 degrees and maximum intensity about 125,000 candlepower. Use of an NIR filter equivalent to Polaroid XR7X25 reduces the intensity to about 40,000 effective holocandlepower. A beam spreader may be inserted to increase the hpi width to 10 degrees.

The light is modulated at 90 cycles by passage through two opposing 90-degree slots cut in a cylindrical tube or chopper rotating about the lamp. The chopper is driven by a 24-volt, 2,700-rpm, d-c, governor-controlled motor. The lamp and motor are in a vertical chimney ventilated by a blower on the motor shaft. The receiver is carefully shielded from the source by light-tight joints except for a small out-of-phase controlled leak used as compensation for atmospheric backscatter (see Section 4.1.3). Backscatter from local objects is cut down by placing an extension tube out in front of the Fresnel lens, as shown in Figure 18. The receiver consists of a type A TF cell mounted axially at the focus of a 12-inch diameter, 2½-inch focal length Alzak aluminum reflector, with about a 15-degree hpr angle of view. The preamplifier, amplifier and tuned filter circuit are of the design used in the type D development in late 1943 (see "Preamplifier" under Section 5.2); the response peaks at 90 cycles with a 5-cycle bandwidth.

An output transformer may be used to operate either headphones or a neon indicator lamp, preferably the latter. The transceiver is mounted in gimbals permitting an angle of swing of 70 degrees. The total weight together with a small control and indicator panel is about 115 pounds in the laboratory model. A telescopic aiming sight is provided.

The retrodirective triple-mirror reflectors, shown in Figure 19, were furnished by Section 16.5, NDRC. Each consists of a tetrahedral glass prism with

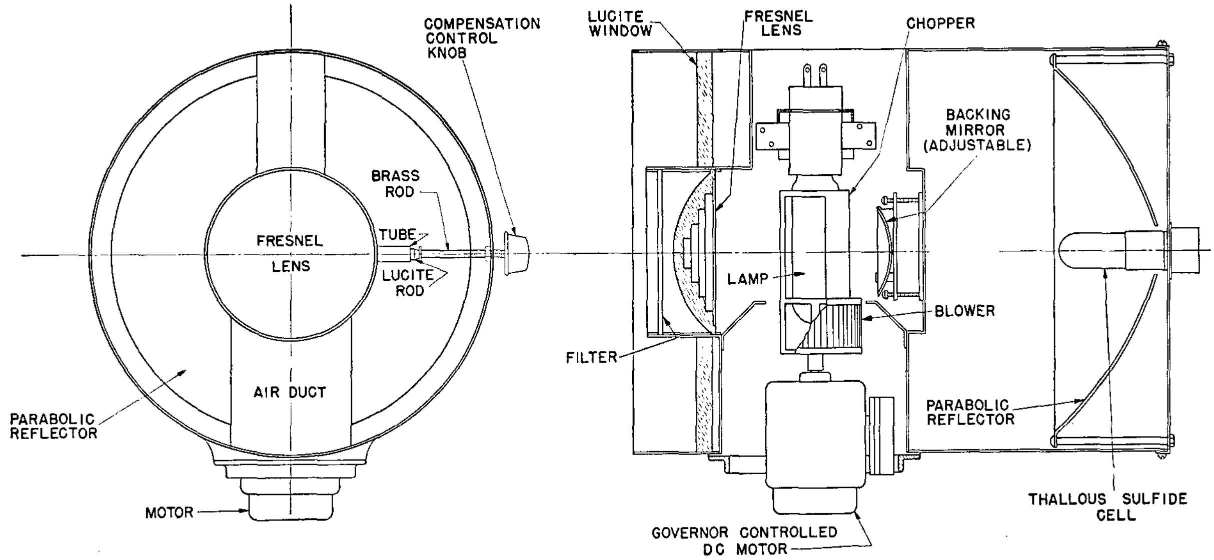


FIGURE 17. Design of RTL transceiver.

three internally reflecting silvered faces which form the corner of a cube. An incident beam is reflected three times in such a corner to return accurately along its initial path. This effect is commonly used

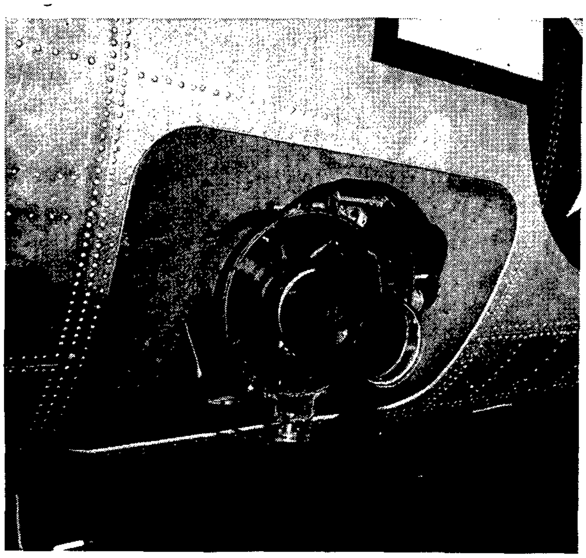


FIGURE 18. RTL plane installation, exterior.

in highway markers and signs to reflect lights from auto headlights back to the driver. The effective entrance angle of these mirrors is about 90 degrees wide; six to eight reflectors will give complete coverage over a hemisphere, as for use on a life raft. The effective diameter of the active face of one mirror is about 40 mm, and the diffraction width of the reflected beam from a face of this area is comparable to the allowed deviation of 5 seconds. This deviation corresponds to 1.5 inches per mile, so that the reflected beam from the transmitter used here falls completely within the receiver at distances up to at least two miles. Each mirror weighs about 0.25 pound. Several mirrors may be mounted adjacently to give increased intensity.

The largest ranges are obtained when the beam is interrupted at the mirrors by a rotating sector disk, as shown in Figure 19. The motor actually

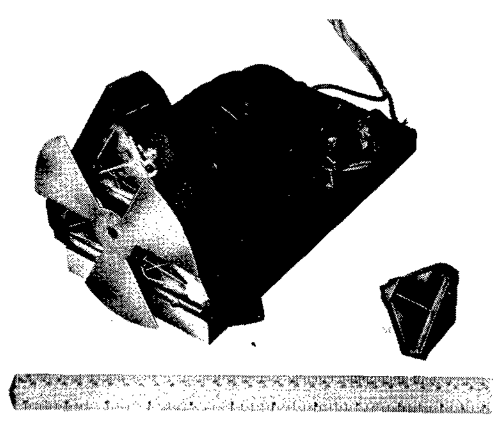


FIGURE 19. RTL reflector modulation unit.

used with the three-bladed sector disk shown was a 24-volt, 1,800-rpm, governor-controlled, d-c motor.

Security. The filter used for the NIR studies was

equivalent to Polaroid XR7X25. A rough computation indicates that the maximum NVR is of the order of 200 yards. The filtered beam intensity is about 30,000 holocandlepower, about 10 times as strong as type E and 100 times type D, with the result that the maximum ACW range of observation of the source by an infrared electron telescope such as the C_3 or C_4 must be quite large, of the order of 10 miles for the 4-degree beam.

The RTL system has some unusual security features, because the reflectors can be detected over a very wide angle, but *only* from an observing point within a few inches of the transmitter beam. They are inconspicuous in the daytime, and enemy capture would reveal a minimum of information as to their mode of use.

Range. With the array of three reflectors shown in Figure 19 the ACW night ranges of the working model appear to be about as follows between ground or ship stations:

Beam width	Source Modulated (with compensation for backscatter)	Reflectors Modulated
4° no filter	2.5 miles	4.5 miles
Filter		3.5 miles
10° no filter	2.0 miles	3.5 miles
Filter	1.5 miles	2.5 miles

Due to various operating difficulties, some of which might be present in actual use, no range from an airborne transmitter of 10 degrees hpi width to a ground reflector was obtained greater than about 1 mile. Daytime ground ranges were less than 0.5 mile.

Evaluation. The working model was designed to give only order-of-magnitude range determinations to guide further plans and not absolute limit ranges for this type of equipment. How much the improvements made in the type D receiver sensitivity in the past two years would improve the performance of the system is unknown.

All reflection systems such as this system or IRRAD (infrared radar, Chapter 6) involve a double attenuation of the light beam since it traverses the path twice; also the inverse square law (Section 4.1.3) generally, though not always, operates over both paths, giving an inverse fourth-power law with distance, in addition to the attenuation. As a result, while a one-way system like type E (Section 4.4.2) has a loss of signal near its operating limit at the rate of about 7 db per mile in average clear weather, the RTL system has a rate of loss near its operating limit of about 20 db per mile. Even with considerable improvement in performance, it therefore seems unlikely that the ACW range of the RTL system, with the modulated source, would increase much beyond 4 miles or, with the modulated reflectors, much beyond 5 miles. It should be possible to increase the air-to-ground (or water) range by use of a slower plane (that in the tests had a cruising speed of about 180 mph) with provision of a large field of view and certain automatic helps for the operator. Daytime ranges up to 1 mile could probably be obtained with slight revisions in design.

It would therefore appear that a system of this kind could be made to serve fairly well the purpose for which it was intended.

As already noted in Section 5.1.1, the Navy specifically did not want telescope detection of the reflected beam because such detection would require an extra crew man on the plane for constant searching. However, some observations made during the development throw light on the relative usefulness of a telescopic RTL. It was noted in the tests that at threshold range for the present system, when no filter is used, the reflectors are clearly visible to an observer whose eye is several inches away from the most intense part of the beam. This suggests that a small ordinary telescope substituted for the receiver might give a considerably greater range of detection, and would give a much more direct, certain, and accurately located observation of the reflector than the mere observation of the RTL neon indicator lamp could ever give; and source or reflector modulation would be unnecessary. Judging from image tube versus receiver sensitivities observed with other systems, an infrared electron telescope used with a filtered RTL beam would have a range somewhat less than that with the present receiver; however, it would still possess the other telescope advantages just noted.[c]

Transmitter Details

Compensating Device. The details of the device which compensates for backscatter are rather interesting. A small hollow tube projects radially out to one side of the lamp as shown in Figure 17. In this tube is placed a Lucite rod with a roughened conical taper on the external end. This rod can be pushed

[c] Infrared retrodirective telescope systems are described in Division 16 Summary Technical Report, Volume 4.

in or pulled out of the tube to adjust the amount of light escaping from its tip to the receiver mirror. The hollow tube may be moved laterally to adjust the phase of the compensating light so it is exactly 90 per cent out of phase with the transmitter beam. The amount of compensation must be changed with changing source location and weather conditions. During an operation the amount of compensation is adjusted so that the signal is a minimum when none of the triple mirrors is in the field of view. Frequent adjustment of the compensation is required on account of changing atmospheric conditions and it should be made automatic in any equipment designed for actual field use.

Operational Tests

Tests over Land. Many night tests were carried out in 1943 over land from a transceiver in a seventh-floor room in the University Hospital in Ann Arbor, Michigan, to a series of reflector stations from 0.2 to 5.3 miles away down the Huron River Valley. If the signal from a given station were above threshold, it could be reduced to threshold by reduction of the source candlepower with a calibrated rheostat. The amount of reduction required was an indication of the additional range to be expected with full source power. The resultant threshold ranges, corrected to ACW and averaged, are roughly as given above under "Range," for receiver modulation. For source modulation, all of the additional range indicated by this procedure cannot be used because the local backscatter increases as the source power is increased to its full value; even with compensation, the noise level rises. Estimated suitable corrections to take account of this situation were included in computing the range values previously given for source modulation.

Some uncertainty in these measurements was introduced by train smoke from a nearby railroad. It was noted that operation through snow or rain was impossible because of the strong noise produced by pseudomodulation of the backscattered radiation by the falling drops or flakes.

Tests at Patuxent River Naval Air Station. With the cooperation of BuAer, the transceiver was mounted on a modified port hatch cover of a B–26 type medium bomber and used in day and night tests to reflectors on the ground from altitudes of 1,000 to 5,000 feet. These tests were carried out from December 29, 1943, to January 1, 1944, inclusive.

The transceiver had a vertical traverse of about 70 degrees which limited the time for identification of the target by the operator and hand aiming of the equipment to little more than 5 seconds at the plane speeds and flight altitudes used. The field of view of the operator was very limited and was different from that of the pilot. The result was that very few runs made successful contact. Night contacts were obtained only at ranges under 6,000 feet. No successful contacts at all were obtained in the daytime.

The night ranges are less than the values over land previously noted, partly because of the experimental difficulties and partly because of overcast cloud layers near the working altitudes, which would not have interfered with operation between land stations. The apparatus appeared to function almost as well in the plane as on the ground. Daytime identification was impossible because of high and irregular background illumination (about 1,000 foot-candles) from the snow-covered landscape. One daytime test was made at 1,000 feet altitude over a reflector mounted on a small boat on Chesapeake Bay. This was unsuccessful.

Subsequently, a theoretical study was made of optimum relations between scanning angle and rate, plane velocity and altitude, and beam width for most efficient search from a plane (as for survivors at sea) with an instrument like the RTL.[10]

Tests over Water. Additional tests were made January 6, 1944, from the RTL unit on a low bluff to retrodirective mirrors on a small boat in Chesapeake Bay. The night was clear and the ranges obtained agree very well with those given previously under "Range" for measurements over land.

Present Status

Nothing further was done with the RTL following these tests, because at that time the Navy felt that radar methods offered greater promise and precluded the addition of other equipment on planes already heavily loaded.

Recommendations

The principles of retrodirective location with triple mirrors should be extremely valuable for both military and civilian purposes. The RTL equipment demonstrated the feasibility of one possible mode of application.

5.5 JAPANESE INFRARED DETECTION [JAPIR] SYSTEM

Description and Performance

Course of Development. In 1944 Navy observers reported that the Japanese air forces seemed to be successful in assembling during night operations without the use of detectable radio or visible signals. This suggested that they might be using infrared recognition or signaling devices. Project Control NA–191 was therefore set up in July 1944 under Contract NDCrc–185 at the request of BuAer to develop and construct four sets of equipment for aircraft installation to detect such infrared signals if they were being used.[11-13]

These units were to give automatic instrument panel presentation, were to be bore-sighted with the guns with hpr width of 6 degrees, and were to have minimum weight, power consumption, and aerodynamic drag. A threshold sensitivity of 0.1 mile-candle (about 10^{-9} lumens for a 7-inch mirror) was requested, but, of course, is out of the question with present detector cells with a suitable bandwidth in any feasible size of reflector (see Sections 4.1.3 and 4.4.2). In absolute darkness, a sensitivity of about 5 modulated mile-holocandles (see the Appendix) was actually obtained with the apparatus built. The incident flux on the cell with this signal is less

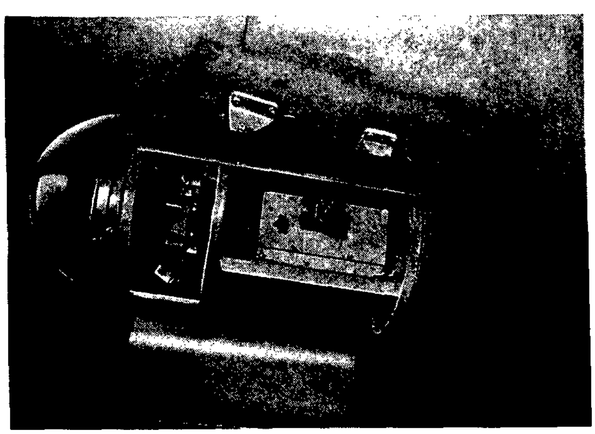


FIGURE 20. JAPIR nacelle, mounted on wing, covers removed.

than $\frac{1}{10}$ of the incident NIR flux from a clear moonless night sky. Because of this light from the night sky, under actual operating conditions the threshold may be increased to 50 mile-holocandles or more.

One unit was mounted in a nacelle on a Grumman Hellcat, as shown in Figure 20, and flight-tested at the Patuxent River Naval Air Station. Six complete units were constructed and furnished to BuAer in 1945. Two of these were intended for spares.

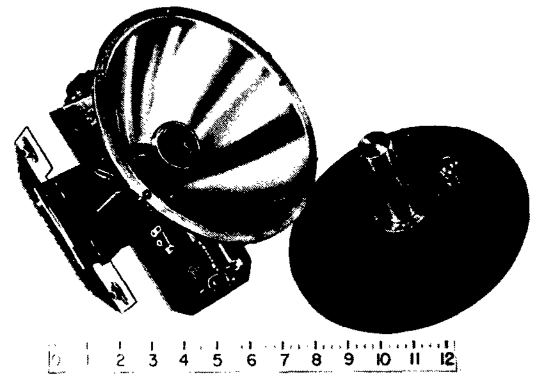


FIGURE 21. JAPIR reflector-motor unit, with filter.

General Design. A JAPIR unit consists of a receiving head, amplifier, and indicating light. The head (Figure 21) contains a $\frac{1}{4}$x$\frac{1}{4}$-inch TF cell mounted axially at the focus of a $7\frac{1}{4}$-inch diameter, 1-inch focal length Alzak aluminum mirror, giving an hpr angle of view of about 6 degrees. The cell is supported on a Lucite disk, coated with an infrared transmitting film filter which covers the mirror. This filter has a short wavelength cutoff at 0.8 μ, which reduces the effect of moon and sky light but has little effect on an already filtered NIR signal.

The cell fits inside a light chopper, which is a cylindrical bakelite tube concentric with the axis of the mirror. The tube has two opposing 90-degree sectors cut out of it and can be rotated by a 28-volt, aircraft-type, 3,600-rpm, d-c motor mounted behind the mirror so as to interrupt an incoming beam at 120 cycles. The chopper provides an a-c component in the amplifier pass band between 60 and 500 cycles, in case the enemy infrared source being sought is either unmodulated or is modulated with frequencies outside this pass band (as in voice communication). A switch on the control panel provides for stopping the chopper and holding it in the open position if it is desired to receive signals modulated in the pass band, or for stopping it and holding it in the closed position for protection of the cell against sunlight when the equipment is not in operation.

A small low-voltage lamp mounted close to the cell (Figure 21) may be turned on with the chopper running to check cell sensitivity and operation of the equipment in the field. The preamplifier, mounted with the receiver head and chopper motor in the nacelle shown in Figure 20, consists of a cathode follower and one stage of amplification. A shielded cable connects this to the amplifier control panel in the cockpit. The latter has a sensitivity control and a high-gain pentode stage and finally feeds a small neon glow lamp on the airplane's instrument panel.

The filament current is taken from the plane's 28-volt d-c supply; the plate and TF-cell voltages are furnished by Navy B batteries. The power requirement is 65 watts with the chopper motor running and 8 watts with it off. The weight of the whole equipment, including connectors and cable, is 25 pounds.

Sensitivity. In absolute darkness the threshold sensitivity is about 5 modulated mile-holocandles. Under filtered unmodulated night sky light, the sensitivity may be less (threshold greater) by a factor of 5 or 10. If the signal and the night sky light must both be modulated by the local chopper, the signal sensitivity is still less.

The order of magnitude of the maximum possible range of detection of an enemy NIR aircraft source may be estimated from the candlepower of strong American NIR aircraft transmitters. The 1,400-hcp P–G transmitter (Section 4.4.3), for example, if modulated below 600 cycles, should be detectable in the center of the beam by JAPIR equipment to about 30,000 yards vacuum range, 10,000 yards ACW range. The Patuxent River plane-to-plane detecting tests, to be described later, gave a range of detection on moonless nights of 3,000 yards when the source was a mechanically coded 240-watt airplane headlamp enclosed in a red glass H globe. This range was considered satisfactory. Moonlight seriously interfered with the operation of the equipment. Actual detection ranges under combat or nightfighter conditions evidently will depend strongly on sky conditions, beam widths and directions and on the circumstances of the encounter.

Evaluation. The JAPIR system fills all the initially requested military characteristics except sensitivity, and it has as high a sensitivity as is feasible at present or useful with the specified beam width under night sky illumination. It is not especially suited for detecting voice systems, but it may be that the system represents a suitable compromise between maximum chopper frequencies, common voice frequencies, and narrow bandwidth.

Receiver Details

Cell Arrangement. To avoid large spurious signals from capacitance effects when the chopping shutter is rotating, the cell is surrounded by a tight-fitting metal shield. The chopping shutter is made of bakelite for the same reason. The metal shield is solid except for the areas through which the radiation passes, which are covered by wire mesh. In the first model the NIR filter was placed directly around the shield, but sunlight focused by the mirror burned the bakelite chopper at some time when the outside fabric cover of the unit was left off in the daytime. In the final models the filter is therefore over the front of the mirror to reduce the intensity of sunlight which may come in accidentally in this way.

Chopper Orientation. When the chopper motor is turned off, after a few seconds' time delay to allow it to stop rotating, a solenoid-ratchet arrangement pulls the chopper shutter slowly around. The solenoid current passes through a slip ring on the motor shaft, until an insulated portion of this ring comes under the brush contact. The shutter then stops in the open or closed position, depending on which of two brushes the current passes through; the brushes are selected by a switch at the control panel.

Preamplifier. The mounting of any low-level audio-frequency vacuum-tube amplifier in an airplane is a difficult problem because of vibration. In particular the cathode-follower stage next to the cell does not amplify the signal, but does amplify the microphonics. To prevent increases in noise from this cause the preamplifier was placed on soft rubber mountings to give the system a natural frequency below 10 cycles. The low vibration frequencies are then cut out by the amplifier pass band. Amplitude-limiting stops on the mountings prevent excessive strains from landing shocks.

Since a single battery provides all the plate supply and cell voltages, decoupling filters are required in the circuits to prevent regeneration. The 10-megohm load resistor for the TF cell is a commercial composition resistor chosen for low noise. In order to keep the operating controls at a minimum this resistor and the cell voltage were not made variable. A voltage divider is used in the high-gain triode stage following the cathode follower, to adjust the overall amplification to the desired value. A low-

impedance stage follows the triode to permit transmission over the shielded cable to the amplifier.

Amplifier. The neon glow lamp could be operated directly from the plate of the high-gain pentode stage, but a low-impedance stage is inserted between them to reduce insulation difficulties when the equipment is used in the moist tropics. Operation is on the linear part of the amplifier characteristic curve for signal voltages near threshold. Stronger signals may produce distortion but this is immaterial with the neon-lamp form of presentation.

Test Lamp. The low-voltage test lamp in the receiver head is preset by adjustment of a series resistor, so that with the chopper running it gives a signal on the cell corresponding to a receiver illumination of about 40 sea mile-holocandles. The neon indicator lamp should then be just extinguished at a certain designated setting of the sensitivity dial if the equipment is functioning properly.

Control Panel and Operation. The amplifier control panel was made as simple and compact as possible. Space was found for it and the battery box on the cockpit floor of the Grumman Hellcat used in tests. The panel contains the sensitivity control and four switches: (1) the master switch, (2) the chopper motor switch, (3) the shutter open-close switch, and (4) the test lamp switch.

Operation and minor maintenance is described in the instruction book for operators.[12] When a JAPIR search is to begin, the master switch is turned on and the shutter opened. The sensitivity control is turned to the point where the neon lamp is just extinguished (with no lights in the field of view) except perhaps for occasional flashes. The presence of an NIR modulated source in the field of view then produces a steady glow in the lamp. No further attention is necessary unless the presence of an unmodulated NIR source on a particular target is in question. The chopper motor must then be turned on and the sensitivity control perhaps reset before aiming at the target. If the target source is coded, the indicator lamp will follow the code.

Operational Tests

Early ground tests were made on a clear, moonless night, at a location away from city lights; the light from the stars was found to give a strong signal.

Later, plane-to-plane tests[13] were made at the Patuxent River Naval Air Station on the nights of December 18 and 26, 1944, and January 11, 1945, at altitudes of 4,000 to 6,000 feet. The F6F-3N test plane made range runs on a TBM target plane carrying a 240-watt mechanically coded airplane headlamp bulb enclosed in a red glass H globe on the under side of the tail. Ranges were determined by radar. On the first night, with visibility 6 miles, the maximum range received was 3,000 yards; on the second night, with visibility 10 miles, moonlight interfered and no target indication was observed; on the third, with visibility 8 miles, the range was again 3,000 yards. This range is equivalent to a receiver sensitivity of about 200 mile-holocandles. There was no interference to or from the test plane's other electronic equipment, and engine vibration did not affect sensitivity. As a result of the tests, several minor changes in design were made.

Present Status

The six complete JAPIR units requested by BuAer were delivered under Contract NDCrc-185 in August 1945, and were mounted on chassis built by Patuxent Naval Air Station, preparatory to field tests in the Pacific Theater at the time the war ended.

Recommendations

The JAPIR system has characteristics as nearly like those originally requested as is feasible.

If there is military need, this system might be modified for ship or land use and further adapted for monitoring enemy NIR *voice* communications. It could be adapted for reception of the IIR by simple interchange of cells.

5.6 SUMMARY OF RECOMMENDATIONS

If these studies are to be continued, some particular and general recommendations can be made. The particular ones concern continuation of the work in progress at the termination of the war.

System	Recommendation
Type D	System is satisfactory and first models are in field use, but several improvements are possible, and its interaction and possible amalgamation with voice systems should be considered
Plane recognition	Further tests
Retrodirective locator	None; other possible systems may be superior
JAPIR	None; first models in field use

Many of the general recommendations in Section 4.9 are applicable here.

Because of the strong and troublesome mutual interference between the systems here described—the voice communication systems of Chapter 4 (see Section 4.9 and "Recommendations" under Section 5.2) and other infrared beacon, blinker, and heat detection systems—it would be highly desirable to have the future development of all types of NIR, IIR, and FIR systems for *all* branches of the Service placed under a single directing agency. The function of the agency would be to plan and organize the various projects so that mutual interference and mutual backscatter would be kept at a minimum and so that the possibilities of each apparatus can be developed to its inherent limit without hindrance from other independent (and possibly unknown) developments. The need in this field is now coming to be like the necessity for frequency allocation in the wildcat days of radio broadcasting during the 1920's. Close liaison between projects and branches of the Services is not enough, as is abundantly testified by the parallel and interfering developments of type D, type E, and searchlight systems for ships, and of the separate plane-to-plane voice, plane-to-plane recognition, and non-NDRC plane-to-plane gunsight warning systems.

Military urgency has been a reasonable excuse for this procedure during the war, considering that these systems were only in the research stage and that few of them actually saw any field use, but the validity of this excuse has now disappeared and a conference should be called immediately among the branches of the Services interested in further infrared developments with the object of clearing the situation up at once. Neglect of this can lead to unpleasant and possibly tragic consequences when the field applications of the infrared systems begin to be numerous.

Chapter 6

NEAR INFRARED SYSTEMS FOR DETECTING RANGE AND DIRECTION [IRRAD]

By *Winston L. Hole*

6.1 INTRODUCTION

THE DEVELOPMENT of *infrared range and direction* [IRRAD] equipment was initiated by Western Electric Company Contract OEMsr–766 as a part of an NDRC Section 16.5 program for developing methods of night surveying by infrared. Other aspects of this program are described in STR of Division 16, Volume 4. Since IRRAD does not employ an image-forming detector and can be used for military purposes other than night surveying, the further development of systems of this type was subsequently transferred to NDRC Section 16.4. The IRRAD models described in this chapter were developed by Western Electric Company Contract OEMsr–1267 and University of Michigan Contract NDCrc–185 as Army Project CE–22 and Navy Project NR–103.

Two complete IRRAD models were constructed by the Western Electric Company for experimental use and field trial, one for the Army and one for the Navy. Both were designed for the detection and ranging of high-precision retrodirective reflectors (triple mirrors) and differ principally in the type of power supply from which they are operated. The Army model was designed for battery operation, light weight, and ready divisibility into four man-borne packages. The Navy model was originally closely analogous except in having an a-c power supply unit, but was subsequently modified to permit the mounting of the essential components on a gyrostabilized platform. It thus became the scanning head of a shipboard plan-position-indicating system for detecting triple-mirror targets mounted on other ships.

Only one experimental model of laboratory type was constructed under NDCrc–185. It was designed for the detection and ranging of the ship proper as a diffusely reflecting target, without the addition of highly efficient reflectors of the retrodirective type.

The differences between the two types of target called for some basic differences in design. The general description and field test results for the different types developed for these purposes by the two contracts will therefore be given separately in the sections which follow.

6.1.1 Principles of Operation

The basic principle of IRRAD is identical with that of radar. An infrared pulse having a duration of the order of 1 μsec is emitted by a flash lamp especially designed for this purpose (Section 1.3.1, "Type 300 Microflash Lamp"). If a target is within the range and field of view of the equipment, a small fraction of the energy in this pulse is reflected back to the receiver. Here it is detected and amplified by an electron multiplier tube having an infrared-sensitive photoemissive cathode (see Chapter 3) and finally is presented as a signal on the screen of a cathode-ray tube. The range of the target is determined from the time delay between the emission of the pulse and its reception after reflection. A combination of several factors, namely, the short duration of the infrared pulse, the absence of pickup between the transmitter and the receiver, and the elimination of time delay associated with "transmit-receive" circuits in conventional radar sets, permits accurate range measurements to be made on targets at distances down to a few hundred feet. Moreover, a high degree of secrecy is maintained because of the small angles to which the transmitted IRRAD beam is confined. Also, because the beam can be rendered completely invisible by means of infrared transmitting filters, special infrared detectors not widely used in military field operations are required to detect it. Even with the necessary infrared apparatus the beam can not be detected unless the receiver is oriented in the proper direction during the short period required for the IRRAD equipment to scan a given zone.

6.2 IRRAD FOR RETRODIRECTIVE REFLECTOR TARGETS

The first IRRAD equipment[1] was constructed under Contract OEMsr–766 as a laboratory experimental model to explore the possibilities of obtaining range data with an infrared system utilizing radar pulse techniques. The practicability of the method was demonstrated to representatives of NDRC, the Army, and the Navy at the Bell Telephone Laboratories in New York City on November 18, 1943. A single target located 774 yards from the equipment was repeatedly ranged with a distance error usually less than ±5 yards and a directional error in either azimuth or elevation usually not greater than 0.25 degree.

The promising results of these preliminary tests led to requests by the Armed Services for additional developmental work. Two improved models[2,3] were therefore constructed under Contract OEMsr–1267, one for the Army and one for the Navy. These models, which are similar in most respects, are described in the following sections.

6.2.1 General Description of Equipment

Figure 1 is a photograph of the complete Navy model IRRAD. It consists of a main unit mounted on a tripod and a power supply unit which can be placed at any convenient location near by.

Additional developmental work was subsequently done on a revised Navy model for use with a plan-position type of indication. For this model a special scanning head, containing only the optical elements of the transmitter and receiver, was designed for mounting on a gyrostabilized platform. The Army model closely resembles the Navy model shown in Figure 1 except in the details of the power supply unit, and also in having a special tripod mounting head and cradle provided with accurately calibrated circles to facilitate high-precision measurements of the azimuth and elevation of the targets.

The interior of the main unit is shown in Figure 2, and a functional diagram in Figure 3. However, the optical elements shown in Figure 3 are those used in the preliminary laboratory model and were superseded in the final models by those shown in Figure 4.

Referring to Figure 3, the high-voltage power supply energizes the 0.1-μf condenser mounted in the lamp shield. When the voltage across the condenser reaches the firing potential of the lamp, the condenser discharges through the lamp and a radiation pulse is emitted. The electric synchronizing pulse from the lamp firing circuit triggers the range unit, which delivers an accurately delayed output pulse at a round-trip time interval corresponding to the range in yards marked on the dial of the range unit.

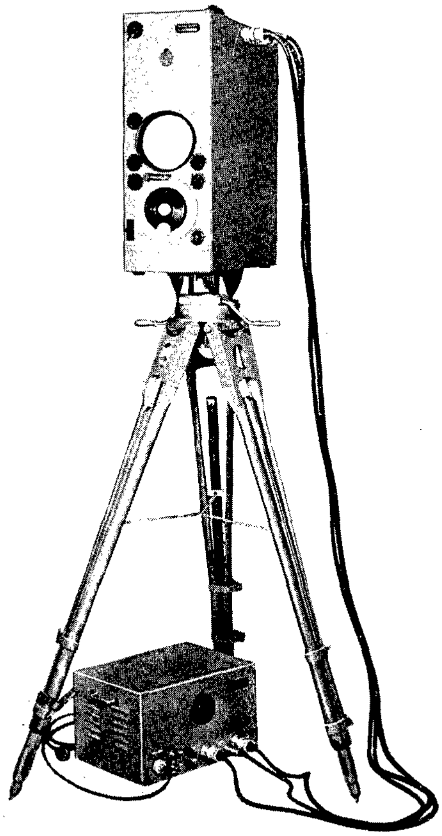


FIGURE 1. Complete IRRAD equipment, Navy model.

The synchronizing pulse also triggers a special high-speed sweep circuit which deflects the cathode-ray beam horizontally. Combined with the sweep circuit is a brightening-voltage generator which intensifies the cathode-ray beam during the horizontal sweep and makes the trace readily visible. The radiation pulse reflected from the target is detected and amplified by the photomultiplier tube and, after additional amplification by a thermionic tube circuit, the electric impulse is applied to the vertical deflection plates of the cathode-ray tube. When the

range unit has been adjusted so that its output pulse coincides with the target-echo pulse on the screen of the cathode-ray tube, the range of the target is read directly from the dial of the range unit, and the azimuth and elevation are read from the circles provided for this purpose. Final "sighting" adjustments in each plane are made by means of slow-motion controls, using the amplitude of the target pulse as the indicator, after the slits in the receiver optical system (items 12 and 13 in Figure 4) have been narrowed sufficiently to yield the desired degree of accuracy.

The dimensions of the cabinet of the main unit seen in Figures 1 and 2 are 24x24x8.5 inches, and the unit weighs about 47 pounds including covers. Layout drawings have been prepared for reducing the size of the unit to 19x19x8.5 inches with an estimated weight of less than 30 pounds. The power supply for the Army unit operates from a 12-volt storage battery and weighs approximately 28 pounds. The current drawn by this power supply when the lamp is not flashing is about 5 amperes and the average total current with the lamp flashing 55 times per second is about 11 amperes; the power actually delivered to the main unit divided by the power drawn from the battery indicates an overall efficiency of about 70 per cent. The power supply unit for the Navy model is operated from 115-volt,

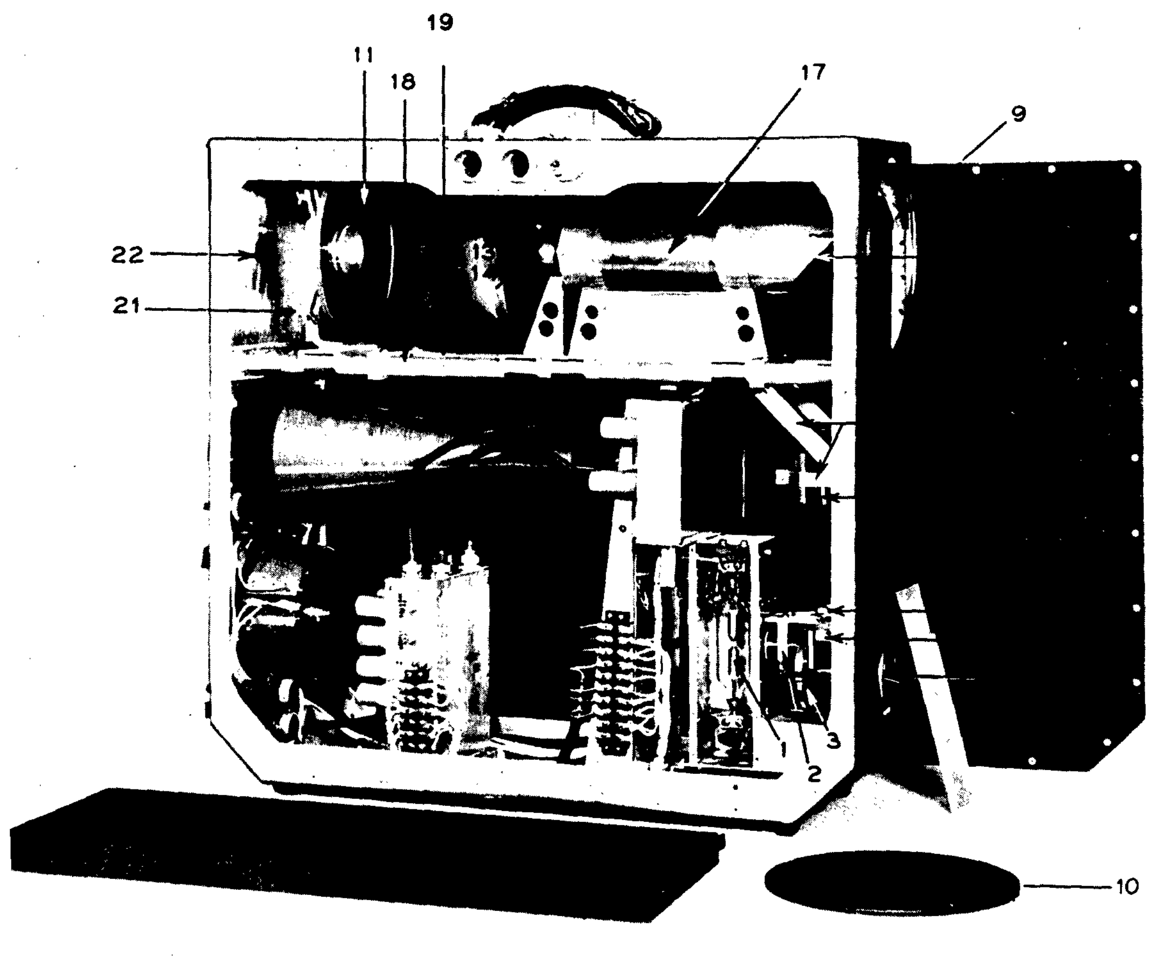


FIGURE 2. Interior of main unit, covers removed. (Key to numbers is given in Figure 4.)

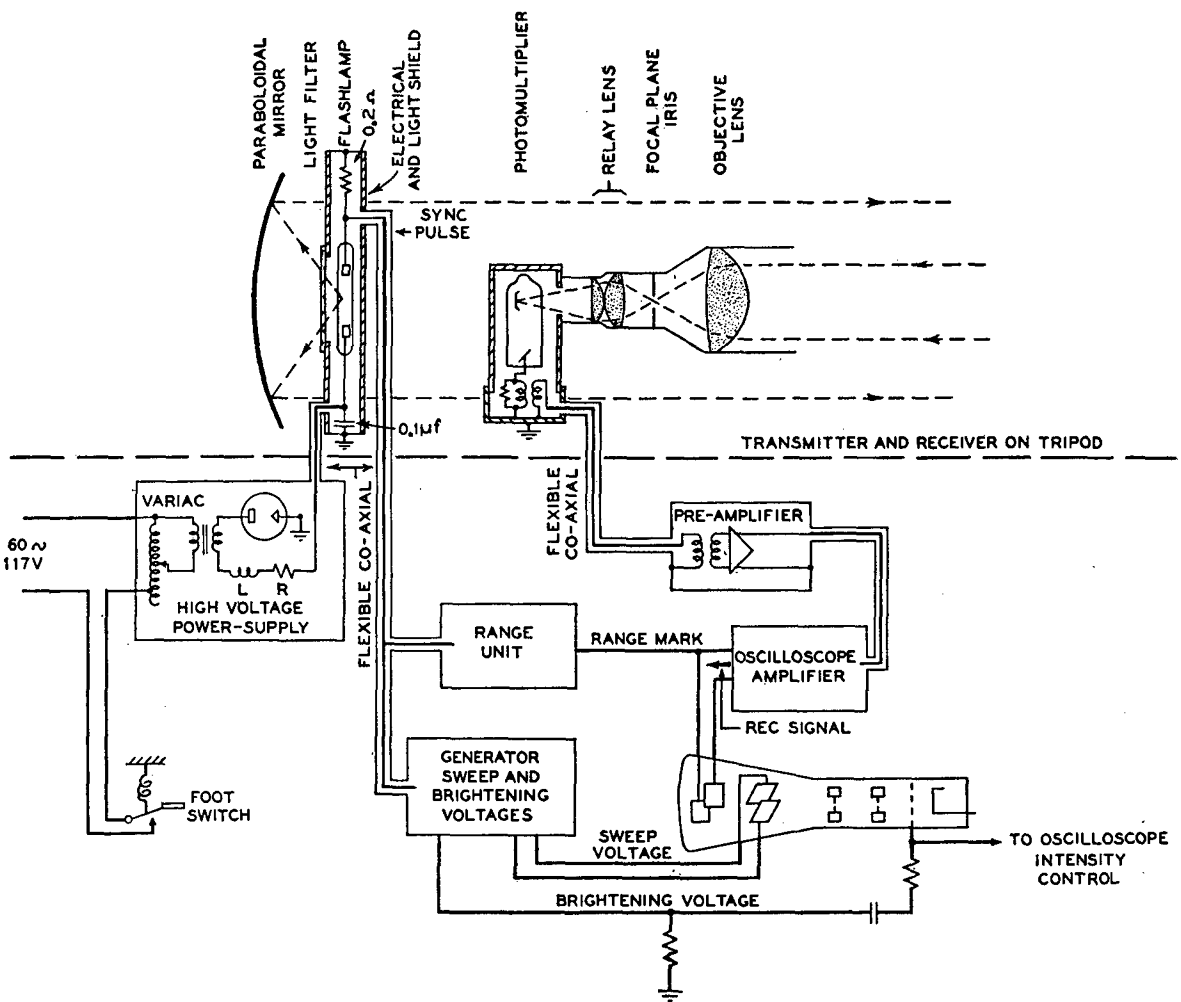


FIGURE 3. IRRAD functional diagram. (See Figure 4 for revised optical schematic.)

60-cycle alternating current. The average total power consumed with the lamp flashing 60 times per second is approximately 175 watts. If desired for Army use also, this same power supply unit could be operated, for example, from an a-c dynamotor driven from the battery of a truck or jeep. The a-c power supply weighs approximately 55 pounds.

It was originally requested in Army Project CE-22 that the total weight of the equipment should not exceed 50 pounds and should be capable of being broken into two loads, neither of which should weigh more than 35 pounds. Although it was impossible to adhere rigidly to these limitations on weight, the Army model was designed to be subdivided for portability into four manborne packages, no one of which would necessarily exceed the 35-pound limitation in a final model. These packages include a small 12-volt storage battery and a tripod mount with transit head, in addition to the main unit and the power supply mentioned above. Although the total weight of the equipment demonstrated at the Army Engineer Board, Fort Belvoir, Virginia, was 148 pounds, the weight of certain components was subsequently reduced and a reduction in the weight of certain other components is known to be feasible.

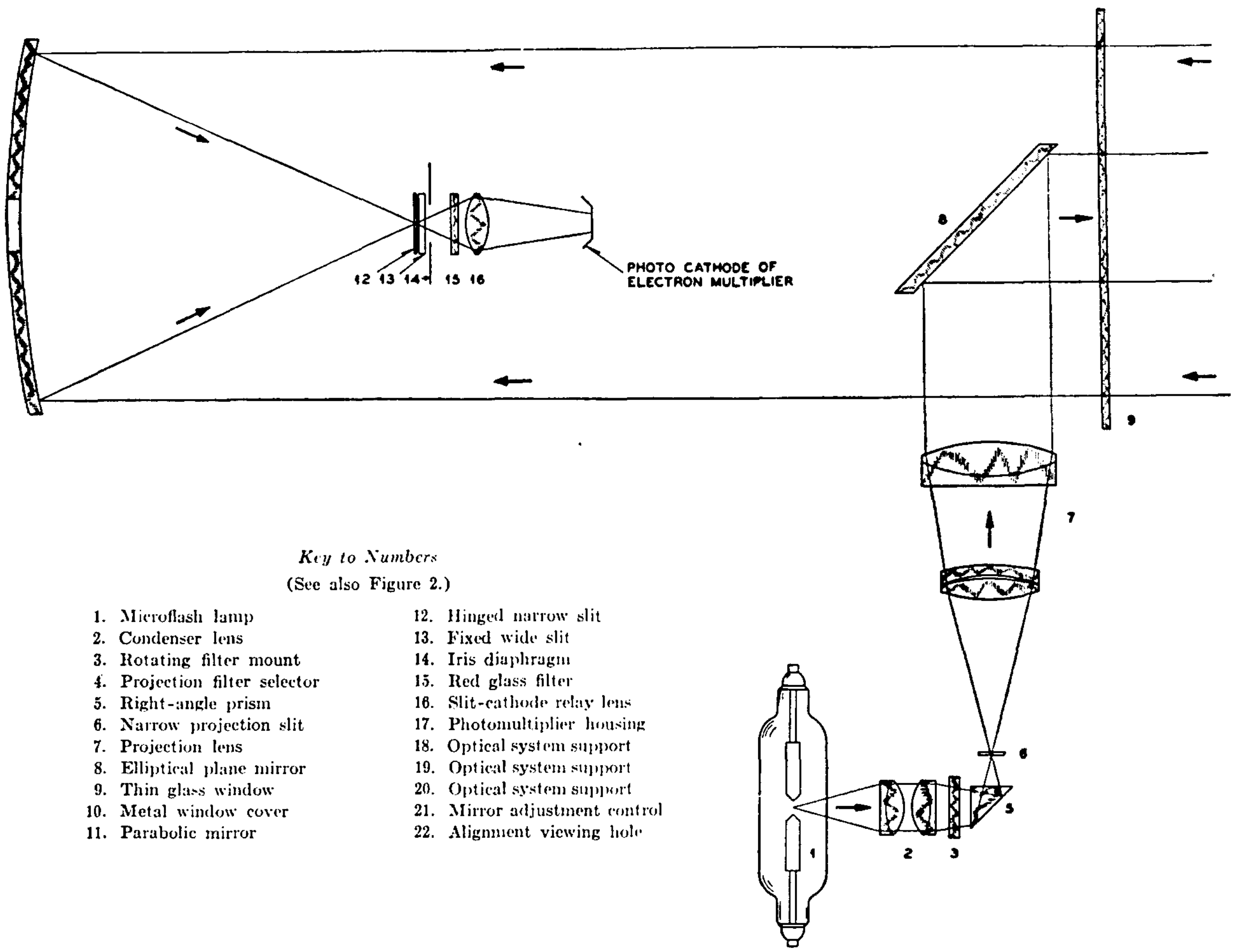
6.2.2 Components of the Main Unit

TRANSMITTING OPTICAL SYSTEM

The transmitting optical system shown in Figure 4 consists of a short-gap, double-ended microflash lamp (Section 1.3.1, "The Type 300 Microflash

Lamp"), a condensing lens system, an infrared transmitting filter, a right-angle prism, and a narrow fixed slit located in the focal plane of the projection lens system. An elliptical first-surface plane mirror mounted at a 45-degree angle on the axis of the receiver optical system reflects the transmitter beam in a direction parallel to the axis of the receiver. With the components located in this manner the accurately coaxial alignment of the transmitter and receiver optical systems needed for effective utilization of the highly accurate retrodirective triple mirrors is maintained. In addition the area of the receiver mirror obscured by components of the transmitter is reduced to a minimum with a consequent increase in optical efficiency and operating range. A thin, clear glass window in the case of the unit provides weather protection for the aperture and is in turn protected by a metal cover while being transported.

The desired infrared filter is selected by means of an external control which rotates a mount containing space for three filters. The filters actually used were Wratten 87 and Polaroid XR7X26, each cemented between clear glass plates, and a clear glass dummy for use in daytime or at night if visual security is not required. The extent of the projected beam, determined by the constants of the transmitter slit and projection system, is 2.5 degrees in the vertical plane and 24 minutes in the horizontal plane. The vertical extent of the beam is ultimately limited by the length of the arc gap in the flash lamp, while the horizontal extent may be changed, within limits, by varying the width of the slit. For use on a rolling ship, even with a stabilized plat-



Key to Numbers
(See also Figure 2.)

1. Microflash lamp
2. Condenser lens
3. Rotating filter mount
4. Projection filter selector
5. Right-angle prism
6. Narrow projection slit
7. Projection lens
8. Elliptical plane mirror
9. Thin glass window
10. Metal window cover
11. Parabolic mirror
12. Hinged narrow slit
13. Fixed wide slit
14. Iris diaphragm
15. Red glass filter
16. Slit-cathode relay lens
17. Photomultiplier housing
18. Optical system support
19. Optical system support
20. Optical system support
21. Mirror adjustment control
22. Alignment viewing hole

FIGURE 4. Optical schematic of IRRAD for retrodirective reflector targets.

form, a somewhat wider beam than 24 minutes may be required. Means are provided for both axial and lateral adjustments of the source, and for axial adjustments of the condenser lens, slit and projection lens.

All optical elements of transmitter and receiver are coated for minimum reflection loss at 0.9 μ and are mounted on two rigidly connected cylindrical tubes and a supporting structure.

Target. One or more of the autocollimating, trihedral retrodirective triple mirrors (see STR Division 16, Volume 4) used as targets is mounted on the object or at the place for which range and direction are desired. Two sizes, nominally rated at 40-mm and 80-mm aperture, have been used. For field use they are mounted in waterproof spun-metal housings. In order to provide protection from chance visual observation the reflectors are sometimes covered with Wratten 88A filter material cemented directly to the face of the prism under an optically flat cover glass approximately 10 mm thick.

Receiving Optical System

The receiving optical system, also shown in Figure 4, consists of a second-surface glass parabolic reflector which forms an image at its focal point; two slits mounted at the focal plane; an adjustable iris diaphragm; a red-glass light filter; and a lens which projects the image formed at the slit onto the cathode of the photomultiplier tube.

Item 12 in Figure 4 is a thin metal plate containing a slit 0.010 inch wide. It is mounted on hinges so that it can be rotated out of the optical path by means of an external control. An adjacent fixed plate, item 13, contains a slit 0.040 inch wide. The wide slit is used during the initial search for a target and the narrow slit replaces it for making azimuthal settings after the target is located, since it further restricts the field of view and thus permits a more accurate reading. An iris diaphragm, item 14, is located immediately beyond the slit. Like the slits it is expanded during the search and contracted by means of an external control for the final setting for angle of elevation. The minimum diameter of the opening in the iris diaphragm is 0.30 inch, which limits the accuracy in setting vertical angles to about ±5 minutes of arc. A diaphragm having a smaller minimum aperture would decrease the residual error from this cause. On the other hand it may be necessary to use much wider slits and to adopt other measures for increasing the angle of view in order to provide satisfactory continuous performance of a shipboard installation, unless a very highly stabilized platform is provided.

The narrow slit subtends a vertical angle of 2.5 degrees and a horizontal angle of 4.5 minutes, while the corresponding figures for the wider fixed slit are 2.5 degrees and 18 minutes. Since the horizontal angular width of the transmitter beam is 24 minutes, small errors in the axial alignment of the transmitting and receiving optical systems may exist without decreasing the amplitude of the signal received during search for a target. Also, since the circle of confusion of the parabolic mirror is only 0.008 inch or less, the image of a distant target will pass through the narrow slit without loss. Repeated azimuthal settings on a distant target show errors ordinarily not greater than approximately ±2 minutes of arc, as would be anticipated when using the narrow slit with its 4.5-minute horizontal field of view. A somewhat higher accuracy of setting might be obtained by using a mirror of still greater precision and a somewhat narrower slit.

The function of the red-glass filter, item 15, is to reduce the interference and multiplier noise which arise from scattered light during daytime observations.

A number of 14-stage photomultiplier tubes having infrared-sensitized cesium-surface cathodes were constructed for this project by the Farnsworth Television and Radio Corporation under Contract OEMsr-1094 (see Chapter 3). All the tubes used for the field tests reported in this chapter have end view cathodes. The tube is mounted on the axis of the receiver mirror in a cylindrical metal shield approximately 2.5 inches in diameter. Since it lies behind the plane mirror (item 8, Figure 4) of the transmitting optical system, it adds very little to the area of the receiver mirror that is necessarily obscured. At first it was hoped that the multiplier would provide sufficient gain to operate the vertical deflection plates of the cathode-ray tube without additional amplification, but this proved not to be the case. Many variations in constructional details were tried experimentally in an attempt to secure improved overall operating characteristics. For example, a 10-stage sideview tube appeared to offer considerable promise near the end of the contract period.

The average amplification per stage for a 14-stage

tube may be as much as a factor of 3 for an applied d-c voltage somewhat in excess of 100 volts per stage. Under such conditions the total amplification of the tube is nearly 134 db. Voltage is supplied to each multiplier stage from the appropriate tap on a potential divider consisting of bleeder resistances in series and a small condenser connected in parallel with each resistance. This arrangement permits the use of high-resistance bleeders, since the bleeder current need be only a fraction of the maximum multiplier current at the peak of the short duration radiation pulses. Possible damage to the tube due to excessive steady illumination of the cathode is thereby prevented, while the potential distribution is restored to equilibrium during the relatively long intervals between IRRAD pulses.

Radiation from the core of a type 300 lamp is narrowed by the transmitter slit and filtered before reaching the photomultiplier tubes. Typical ehT values are 50 per cent for a Wratten 87 and 10 per cent for a Polaroid XR7X26. For one good representative tube tested in darkness in the laboratory, the signal equivalent of noise (see the Appendix) at a pass-band width of 1 megacycle was found to be approximately two equivalent microhololumens. This figure indicates an order of magnitude for the lowest value of signal flux which would be detectable with the IRRAD equipment under ideal conditions. When the Wratten 87 filter is used in the transmitter, the extreme range of visibility for an observer looking directly into the unit is about 400 yards; with the Polaroid XR7X26 filter, the beam is completely invisible to the dark-adapted eye at any distance.

Receiver Circuits

Signal Amplifier. In order to provide accurate transmission of the electric pulses generated from the extremely short radiation pulses, a low-output impedance of approximately 3,300 ohms is used in the collector circuit of the photomultiplier tube. The peak signal voltage available across this impedance without overloading the multiplier is about 0.5 volt. Additional amplification of some 40 db is required to obtain a vertical signal deflection of 0.5 inch on the cathode-ray tube. This is provided by a 2-stage, wide-band signal amplifier using miniature pentode tubes. The heaters of the two tubes are connected in series for operation either from a small 12-volt battery or from a 12.6-volt a-c supply. Plate circuits of both stages contain inductance to extend the high-frequency response as well as supply filters to maintain the low-frequency gain. The amplifier is constructed on a small chassis mounted at one end of the cathode-ray tube circuit compartment, just below the output end of the photomultiplier tube. Short leads and careful shielding are required to avoid pickup of transients from the flash lamp circuit.

A range index pulse of adjustable amplitude and negative polarity, introduced across a cathode resistor in the second stage, appears at the output with the same polarity as the signal pulses. The combination of cathode bias with negative grid bias places the operating point of the tube near cutoff. For this reason the components of the noise input having polarity opposite that of the signal are limited at the second grid.

Cathode-Ray Tube and Control Circuits. A type 5HP1 cathode-ray tube with a green, medium-persistence screen was selected for the IRRAD equipment. This tube has a rating of 2,200 volts between cathode and accelerating anode and a deflection plate sensitivity of about 80 volts per inch. A sweep expansion of about 6 μsec per inch makes it possible to display the entire calibrated range of 4,500 yards on the 5-inch screen when the range dial, which in effect moves the trace horizontally across the screen, is set at its mid-position. Thus a single trace serves to indicate the presence of a target at any range during search. Observed target signals can then be accurately superimposed on the range index, which remains at the center of the screen, by adjusting only the range dial without further adjustment of the sweep circuit.

A cable from the power supply unit carries 6.3-volt a-c leads for the tube heater, and a negative 2,000-volt d-c lead to supply a bleeder consisting of a number of fixed resistors and potentiometer controls for adjusting the intensity and focus of the beam. A voltage-regulator tube connected from a tap on the bleeder to ground provides a negative bias source of about 60 volts for a number of tubes in the range unit and signal amplifier. The deflection plates are connected through high resistances to the regulated potential supply for the accelerating anode, which is 150 volts above ground. Since this voltage is near the balance potential of the sweep amplifier-inverter circuit, good focus of the beam is obtained throughout the trace. The grid of the

cathode-ray tube may be varied from minus 20 to minus 100 volts with respect to the cathode by the manual intensity control on the front panel of the main unit. The grid is also connected to a blocking condenser, through which is fed a positive, square-top pulse from the range circuit. This pulse turns on the beam at the start of the sweep and blanks it out during the retrace and the remaining interval between sweeps.

Range and Sweep Circuits. All components of the range and sweep circuits are assembled and wired in a 5x7x2-inch aluminum chassis which weighs about 2.5 pounds complete. Miniature 6.3-volt heater-type tubes are used with the heaters wired in series-parallel for operation either from a 12-volt battery or from a 12.6-volt a-c supply.

The range circuits consist of a start-stop circuit, an RC time-delay circuit and a coincidence circuit for timing purposes, and a range pulse generator circuit to provide an index on the screen of the cathode-ray tube. These circuits utilize five vacuum tubes and include the range potentiometer mounted on the front panel of the main unit. Four additional tubes are needed for the sweep generator circuit and sweep amplifier-inverter circuit which generate and amplify the horizontal sweep voltages used on the cathode-ray tube. In addition, a neon voltage-regulator tube provides the negative bias voltage required by several tubes in these circuits and the signal amplifier. For circuit diagrams and full details of circuit operation, reference is made to the contractor's report.[2] A brief description of the circuits and of the functions of the components is given in the following paragraphs.

A double triode connected as a biased multivibrator is used in the start-stop circuit. Varistor networks on the flash-lamp housing and in the range unit serve to reduce the amplitude of the negative synchronizing pulse derived from the current through the flash lamp and to clip any positive return or oscillation. The synchronizing pulse triggers the multivibrator circuit, which produces a single rectangular output pulse and then remains cut off until the next synchronized pulse arrives. A deblanking pulse of about 30 volts is taken from the positive rectangular wave on the first plate of the double triode to the grid of the cathode-ray tube. The second plate is coupled to the grid of a pentode in the RC time-delay circuit, causing a sharp cutoff of its plate and screen current at the beginning of the timing interval. During this interval the voltages at both plate and screen rise exponentially with the same initial slope toward the common supply voltage as an asymptote, the time constant of the plate circuit being adjusted for a rise to one-third of the asymptote in the time interval corresponding to the maximum calibrated range of 4,500 yards on the range potentiometer dial.

The plate of the pentode in the time-delay circuit is directly coupled to the grid of a second pentode in the coincidence circuit. The screens of the two pentodes are connected together, the second pentode being normally cut off until the RC timing wave initiates conduction. The time delay before conduction starts is controlled by the setting of the range potentiometer which determines the cathode bias of the coincidence circuit pentode.

The range pulse generator circuit contains two more pentodes. The output of the pentode in the coincidence circuit is amplified by the first pentode in the range pulse circuit, differentiated, and applied to the grid of the second pentode as a positive, steep-fronted exponential pulse of 20 to 30 volts amplitude. This positive pulse causes saturation current to flow to the plate and screen of the second pentode, and the plate drop is again differentiated by a circuit in parallel with the range index amplitude-control potentiometer to form the exceedingly sharp single negative range pulse which appears on the screen of the cathode-ray tube.

The horizontal sweep circuits contain two triodes in the sweep generator circuit followed by two pentodes in the sweep amplifier-inverter circuit. The first triode controls the cathode bias of the second in such a way that the grid cutoff potential of the latter is determined by the range potentiometer setting. This tube is biased so that it is always brought into the conducting region by the RC timing wave a few microseconds before the range pulse circuit tubes in order that the range index will always appear on the sweep trace. A further advantage is that the range index is automatically centered on the screen for all range potentiometer settings, the target signal being carried to the center of the tube when it is aligned with the index to obtain range readings. The sweep amplifier-inverter circuit contains two pentodes and is direct-coupled throughout. Negative shunt feedback is utilized to stabilize the gain, to provide inverter action, and to furnish a reasonably low output impedance into the

cathode-ray tube horizontal deflection plates, thereby minimizing pickup or distortion and reducing the delay in response due to stray capacitance. The voltage to the deflection plates is essentially the same as that from a push-pull amplifier, and both tubes are quite linear for wide excursions away from the balance point.

Wire-wound resistors, silvered mica condensers having close tolerances and ceramicon condensers having a negative temperature coefficient to compensate for temperature drift are used in the timing circuits. The range potentiometer is accurately wound on an exponentially tapered card, so designed that the relation of the resistance to the angle setting of the slider arm matches the exponential rise of voltage at the plate of the time-delay circuit pentode, and thus enables the range dial to have a linear scale. The dial scale contains 450 divisions, the range unit calibration being adjusted to a scale factor of ten yards per division and checked against a crystal-controlled range calibrating circuit during construction. Errors are removed by adjustment of a trimmer condenser. A "zero adjust" potentiometer is mounted on the panel of the main unit to allow the operator during field use to compensate for possible time delay of perhaps a fraction of a microsecond between the synchronizing pulse, the peak of the radiation flash, and the time at which the range pulse generator tubes begin to function.

In setting the "zero adjust" knob a target should be placed at a known distance, say 50 yards, the range dial set for this distance, and the range pulse adjusted to coincidence with the signal pulse on the oscilloscope screen. The best accuracy in range measurements is obtained if the pulses are brought to coincidence in the same manner as for the zero set, preferably coinciding on their steep leading slopes. For this reason each operator should make his own zero set and should check it repeatedly during any series of important measurements.

6.2.3 D-C Power Supply

The d-c power supply for the Army equipment operates from a 12-volt storage battery and consists of two principal parts: (1) the converter, which develops minus 2,000 volts, plus 300, plus 225, and plus 150 volts d-c, and 6.3 volts a-c; (2) the pulser, which energizes the flash-lamp condenser.

Several novel features have been successfully incorporated in the converter. The converter relay is a mechanical oscillator employing a new type of vibrating element which is balanced magnetically and is tuned electrically to have a frequency of about 110 cycles per second. In operation, it sends current from the battery alternately through the two halves of the primary of the converter transformer, thereby setting up alternating voltages in the three secondaries of the transformer. Each secondary consists of two windings, one of which is associated with each half of the primary winding. The vibrator armature and two fixed contacts are sealed in a small glass tube containing hydrogen under high pressure, the entire tube being enclosed by the relay winding. The elements are designed so that the contacts are continuously wetted with mercury from a small reservoir contained in the tube. The mercury insures extremely low contact resistance and also provides "closed transfer" between the primary windings by permitting the armature to touch one contact for an instant before separating from the other as it oscillates back and forth. A novel magnetic structure has been incorporated in the converter transformer in order to utilize more advantageously the closed transfer feature.

The current drawn from the battery by the converter is practically constant. The secondary voltage wave is essentially square and produces a substantially steady voltage at the output of the full-wave vacuum-tube rectifiers used for the minus 2,000-volt and the plus 300-volt supplies, requiring less filtering than a rectified sine wave. Stabilized potentials of 225 and 150 volts are derived from the plus 300-volt rectifier by means of two gas-tube voltage regulators in series. The 6.3-volt a-c supply for the cathode-ray tube filament is furnished by another converter-transformer secondary, properly insulated from ground. Power for the dial light and for the range unit and amplifier tube filaments is supplied directly from the 12-volt battery.

A relay similar in principle to the converter relay is used in the pulser, together with a specially designed airgap transformer having a high step-up ratio. Alternating current from the converter drives the pulser at the same frequency as the converter, but only when d-c bias from the plus 225-volt supply is applied by closing the "send" switch on the front panel of the main unit. Energy from the current which flows through the primary of the

transformer in the half-cycle during which the pulser relay contacts are closed is stored in the air-gap, since a flow of current in the secondary of the transformer is prevented by the polarity of a mercury vapor rectifier connected in series with it. When the pulser relay contact is broken, the polarity of the voltage in the secondary coil is reversed and energy is stored and retained in the flash lamp condenser by the action of the rectifier. This process is repeated until the voltage across the condenser is sufficient to flash the lamp, dissipating the energy stored in the condenser. Under average conditions two increments of charge in succession will cause the lamp to flash, resulting in a flashing rate which is one-half the frequency of the converter (or pulser) relay. The flashing rate may vary with a number of factors such as the battery voltage, the breakdown potential of the flash lamp being used, etc. For example, as the battery voltage drops, less energy will be transferred to the condenser per cycle and more charging increments will be required to fire the lamp, with a consequent decrease in flashing rate. No disadvantage results from this aside from a decrease in the brightness of the trace on the cathode-ray tube screen.

6.2.4 A-C Power Supply

The power supply for the Navy equipment operates from a 115-volt, 60-cycle alternating current. Output of minus 2,000 volts of direct current for the cathode-ray tube and the photomultiplier is obtained from a half-wave vacuum-tube rectifier of conventional design. A full-wave vacuum-tube rectifier, also of conventional design, provides plus 300 volts for the range unit and amplifiers, while stabilized voltages of plus 225 and plus 150 volts for these units are derived from the 300-volt rectifier output by two gas-tube voltage regulators. A 6.3-volt supply for the filament of the cathode-ray tube is furnished by a winding on the 2,000-volt supply transformer. The 12.6-volt supply for the dial light, the flash lamp control relay, and the filaments of tubes in the range unit and amplifiers was obtained, as a matter of expediency, by connecting two 6.3-volt transformer windings in series.

The output of minus approximately 4,000 volts d-c for exciting the flash lamp is furnished by another half-wave vacuum-tube rectifier. The transformer used for this purpose is designed to deliver a small current at high potential and has a large leakage reactance and a high secondary resistance, both of which are utilized to limit the charging current to the 0.1 μf flash lamp condenser. A Variac is used to control the voltage applied to the primary of this transformer and to control thereby the rate at which the lamp is flashed. If the voltage is sufficiently high, the condenser will be charged rapidly enough to fire the lamp once during each cycle. At somewhat lower voltages the flashing rate will be less, and at much higher voltage, greater. However, the most stable and regular operation occurs at the rate of 60 per second or an integral fraction thereof.

6.2.5 Field Test Results

Tests of Army Model

The Army model of the IRRAD equipment was demonstrated at Fort Belvoir, Virginia, on the nights of July 28 and August 8, 1944, to Army, Navy, British, and NDRC representatives. Since further work on the battery-operated power supply was still required, an a-c power supply was used. The targets were triple mirrors of 40-millimeter aperture.

In the first test it was demonstrated that individual targets dispersed in a valley containing trees, shrubs, and other objects could be readily detected with a few search sweeps; that the signal pulse was reduced to half-amplitude by a 2-minute shift in azimuth setting; and that an individual target could be detected and accurately ranged at 4,186 yards using Wratten 87 filter, or at 2,089 yards using Polaroid XR7X26 filter in the transmitter.

Tests on the accuracy of range and azimuth measurement were made on the second night. Two observers rapidly located six individual targets at ranges up to 2,100 yards and measured their range and angle coordinates. The errors of observer A were all within 5 yards in range and 3 minutes in azimuth; those of observer B, who had had no previous experience with the equipment, were within 14 yards and 10 minutes, respectively. Since B's range errors were all positive, it is thought that his readings may have been consistently large due to the fact that he was not invited to make his own zero set, as discussed in Section 6.2.2, "Range and Sweep Circuits."

Tests of Navy Model

Field tests of the Navy model, essentially identical with the Army model except for the a-c power supply, were made in cooperation with the Navy on October 23 and 24, 1944, at the Bureau of Ships Test Station, Fort Miles, Delaware. The IRRAD equipment was set up on the shore. A ship, equipped with a crown of six triple mirrors around a mast to provide a suitable target at all headings, made trips over an agreed course while range-azimuth-time measurements were made at about 100-yard intervals out to the 4,500-yard maximum range of the calibrated dial. The maximum range at night using Wratten 87 filter in the transmitter exceeded the 4,500-yard calibration limit and was estimated from the course and time measurements to be about 6,000 yards. With no filter, successful observations were made to an estimated range of about 7,500 yards, the signal-to-noise ratio being approximately two to one at this distance. The atmospheric transmission was estimated to be about 70 per cent per mile. When the source was covered with Wratten 87 filter, it was invisible beyond about 400 yards to an unaided, dark-adapted eye, but could be seen to nearly 800 yards with 7-power, 50-millimeter binoculars. When the XR7X26 filter was used, the source was completely invisible at any range.

Successful daytime tests were also made along the shore line in bright sunlight. Using Wratten 87 filter over the source, ranges were measured up to the maximum unobstructed distance of 2,100 yards. At this distance the signal-to-noise ratio was about five to one.

6.2.6 Discussion

Tungsten or Mercury Source

Since it is possible by means of mechanically operated components to project short pulses of radiation from a continuously emitting source, experimental systems of this type were constructed and tested before the microflash lamp which was finally adopted had become available. A d-c operated incandescent tungsten lamp was used as the source in two such systems. The first employed a rapidly rotating disk in which narrow slits were cut, and the second employed one rapidly rotating mirror and several fixed mirrors in conjunction with a stationary slit. A high-pressure mercury vapor lamp was also tried as the source in the second system. Although some measure of success was obtained in each case, the accuracy obtainable in range and angle settings never approached that which was obtainable through the use of the short-duration flash lamp. Moreover, it was never possible to establish with the tungsten or mercury source in either system an operating range comparable with that expected on the basis of a comparison of the holobrightness (see the Appendix) of these sources with that of the flash lamp. Although a part of this discrepancy may have been due to vibrations excited by the high-speed rotating elements, the reasons for some of the difficulties encountered experimentally have not been fully established and do not merit further discussion here.

Final Status of Army Model

Following the NDRC demonstration and additional tests conducted by Army personnel, a report [4] on the IRRAD equipment was issued by the Engineer Board of the Army Corps of Engineers. Although the experimental model essentially met the military characteristics for which it was constructed, it was concluded that it did not meet satisfactorily the accuracy and dependability requirements for field use in surveying and that its use in other applications would be limited. In view of the long period which would be required to develop the equipment in such a way as to meet the requirements for widespread field use as a portable, high-precision surveying instrument, and the special training which maintenance men would need, it was recommended that the development be continued by NDRC or other civilian research agency on a long-term, low-priority basis. The principal points of interest for further development were stated to be improved accuracy as a surveying instrument, reduction of size and weight to permit easier transport in manborne packages, and any possible increase in ruggedness and simplicity for field use. No additional development along these lines was undertaken by NDRC.

Final Status of Navy Model

Because of continuing Navy interest, some exploratory work on a plan-position-indicating adaptation was conducted under NDRC auspices. The relations between pulse rate, rotational scanning

rate, and azimuth angle of the projected beam were investigated. The persistence characteristics of the cathode-ray-tube screen demanded that the pattern be reproduced at least once in every four seconds. The pulse rate was increased to 120 flashes per second and all slits were removed from the transmitter in order to utilize the entire width of the flash-lamp discharge, subtending about 1.5 degrees in azimuth. Since the beam subtends only 2.5 degrees in the vertical plane, it was found necessary to mount the scanning head on a gyrostabilized platform. Optical elements of both the transmitter and the receiver were then redesigned to reduce the weight of the scanning head. At the same time improvements were incorporated which promised to extend the feasible operating range to 10,000 yards at night when using the Wratten 87 filter. A circuit was also devised to vary automatically the gain of the photomultiplier tube in such a way as to compensate for variations in signal intensity with range and to achieve nearly equal brightness of the indicating spot on the screen of the cathode-ray tube for targets at all ranges. The special components required for a shipborne installation utilizing this type of signal presentation were furnished by the Navy, and the completion of a test model was taken over by a direct contract, superseding Contract OEMsr–1267. The details of construction and operation of the completed model were not available for inclusion in this report.

Recommendations for Further Development

In view of the high precision in range and direction measurements demonstrated to be possible with existing IRRAD equipments, it is recommended that refinements in the optical systems and in the mode of aligning the index pulse with the signal pulse be added for any adaptation in which such refinements would result in an equipment having considerable value for military purposes at ranges somewhat in excess of 4,000 yards for a single triple-mirror target. Questions pertaining to type of power supply, ruggedness, divisibility into manborne packs and total size and weight limitations should be jointly considered in the light of future military needs. Some improvements appear to be possible in each instance, although successful major alterations in these details will be contingent upon the development of greatly improved components such as flash lamps, photomultipliers, etc.

6.3 IRRAD FOR DIFFUSELY REFLECTING TARGETS

Equipment for investigating the practicability of an IRRAD system for use in the detection of large, diffusely reflecting objects, such as ships against a sea background, was constructed and tested[5] under Contract NDCrc–185. The close liaison already established between this contract and Contract OEMsr–1267 for the development and testing of a suitable microflash lamp source was continued for this development. Since the principles of operation and the required components are essentially identical in the two types of IRRAD systems and since the equipment for detecting diffusely reflecting targets was never carried beyond the laboratory experimental stage, only a brief description of the latter equipment will be given with the points of difference rather than of similarity between the two systems emphasized.

With an extended target having a surface of low reflectance it becomes necessary to abandon high precision of azimuthal angle settings as an objective and to adopt every possible measure which will increase the amount of flux impinging on the target and, therefore, on the detecting element after reflection, in order to achieve operation at a large enough range to be of military value. This difference arises from the fact that the small, highly efficient, triple-mirror target can utilize only that flux which is projected into the very small solid angle defined at the transmitter by the target, which subtends no more than a few seconds of arc at threshold range; while for an extended target all the flux projected into a zone subtending as much as several degrees of arc may contribute to the integrated intensity of the reflected signal. Thus an optical system having a low f/number is advantageous, the focal length being chosen with due regard to the dimensions of the source and the estimated angular extent of the target.

6.3.1 General Description of Equipment

The source used in the transmitter was a type 300 microflash lamp (see Section 1.3.1), with the arc centered at the focal point of a precision, glass, second-surface parabolic reflector of $19\frac{7}{16}$-inch aperture and $7\frac{7}{8}$-inch focal length. Lamps having an arc length of approximately 1 centimeter were

used, oriented with the arc gap transverse to the mirror axis. The angular dimensions of the projected beam were approximately 1x3 degrees, with the long dimension horizontal. The lamp was mounted directly on the firing condenser and was enclosed in a coaxial cylindrical copper shield provided with a suitable optical aperture facing the mirror. The capacitance of the firing condenser was 0.1 μf. The lamp was fired 60 times per second at its self-breakdown potential, using an unfiltered half-wave rectifier as the power supply. Either a Wratten 87 or a Polaroid XR3X44 infrared transmitting filter could be inserted in the cover of the reflector housing. The peak candlepower at the center of the beam, measured through the Wratten 87 filter with reference to a cesium-surface phototube, was about 7.5×10^7 equivalent holocandles.

The receiver optical system consisted of a semi-precision metal parabolic reflector of 18-inch aperture and 7⅞-inch focal length, with the cathode of a 14-stage, end-view, cesium-cathode photomultiplier tube (constructed under Contract OEMsr-1094) located in the focal plane. Because of the construction of the cathode the angular width of the receiver field of view was limited to 1.5 degrees or less over a major portion of the mirror aperture. An 11-stage tube having a cathode and envelope arrangement which was more efficient for this application was later constructed under Contract OEMsr-1094 but was not available for use at the time of the field tests on actual ship targets.

The output of the multiplier was fed through a high-gain wide-band amplifier to the vertical deflection plates of a 5-inch cathode-ray tube. Both the amplifier and the cathode-ray tube power supply were obtained from the Radiation Laboratory of the Massachusetts Institute of Technology, having been originally developed as components for the P-4 synchroscope. A triggered high-speed sweep circuit with trace-brightening voltage generator, constructed according to specifications obtained from Contract OEMsr-1267, was used to control the horizontal deflection and the brightness of the trace. No timing and range pulse circuits were included in this equipment. The target range was determined from the distance between a zero range index and the target pulse on the screen of the cathode-ray tube, a chart for this purpose having been prepared for each sweep speed. Any one of five sweep speeds between 0.75 and 12.3 μsec per inch could be selected at will, as found convenient for measuring the ranges of targets at different distances. The accuracy of range measurements was about ±5 per cent. No provision was made for the measurement of angles of azimuth or elevation, although circles for making approximate measurements of these angles could easily have been added. Also, no attempt was made to hold the weight, size or power consumption of the equipment to minimum values, since the project was on a short-term, exploratory basis.

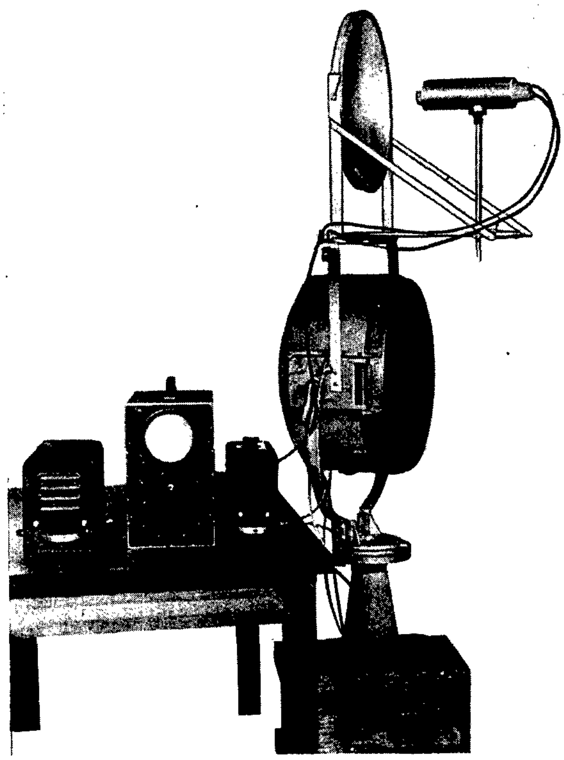


FIGURE 5. Complete IRRAD equipment for diffusely reflecting targets. Left to right: sweep and trace-brightening generator, oscilloscope, multiplier power supply, scanning unit, lamp power supply.

The complete experimental apparatus is shown in Figure 5. The optical components of the transmitter and the receiver were bolted rigidly to an iron framework, thus forming a single "scanning unit" which could be rotated about either a horizontal or a vertical axis. A Polaroid sight was used to check the approximate orientation. The weight of the entire equipment was approximately 450 pounds. All components were designed to operate from a 115-volt, 60-cycle power line.

6.3.2 Field Test Results

Preliminary tests were conducted on the University of Michigan campus with targets consisting of a few relatively distant structures to which an unobstructed view could be obtained. Photographs of traces in which the presence of these stationary targets was indicated are shown in Figure 6. It was found possible to resolve two targets which were simultaneously in the field of view, separated by only about 12 per cent of their mean distance of 1,470 feet from the equipment, and to measure the range of targets at distances from 1,100 to 2,500 feet with an accuracy of about ±5 per cent of the distances obtained from a scale map of the campus. These tests were adversely affected by the large amount of stray radiation from nearby lights to which the photomultiplier cathode was exposed and by the smoke and haze generally encountered during the tests. The high peak at the left of each trace is due to radiation scattered back to the receiver from the atmosphere and nearby objects. There is some evidence for the existence of a time delay in the recovery of the photomultiplier tube from overloading due to the initial backscattering. This delay is long enough to increase the minimum detectable signal, even at the time the target echo pulse is received, due to the persistence of the abnormally high noise level associated with large values of multiplier current. The adverse effects of backscattering could presumably have been diminished if the transmitter and receiver optical systems had been a good deal more widely separated in space. This condition could only be achieved with a much more complicated system, which was not feasible in this experimental equipment.

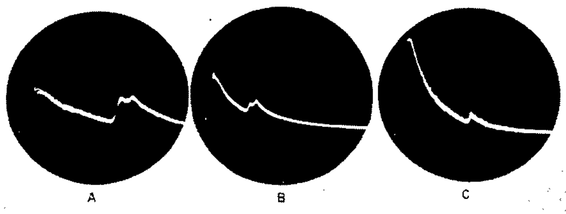


FIGURE 6. Typical oscilloscope patterns (7/50 actual size) for diffusely reflecting targets. A. Target consisted of a pair of red brick chimneys 1,380 and 1,560 feet distant. The exposure includes 120 traces at 0.93 μsec per inch. B. Target consisted of a pair of red brick chimneys 1,380 and 1,560 feet distant. The exposure includes 1,800 traces at 3.3 μsec per inch. Note the increase in backscattering relative to the target echo as compared with A which was photographed on a different evening. C. Target consisted of a part of the University of Michigan Hospital, a white limestone structure with large window areas 2,525 feet distant. The exposure includes 60 traces at 3.3 μsec per inch. This was photographed a few minutes after A.

On the night of October 10, 1944, ship detection tests were made from a station on the shore of Lake St. Clair at a point about 15 feet above the water level, using Great Lakes freighters as targets. Their hulls are invariably dark, with an estimated reflectance of only about 5 per cent. However, at bow and stern there are small superstructures which are ordinarily painted white and have an estimated reflectance of about 75 per cent. The average height above the water line may vary from about 12 to 25 feet, depending on the ship and how heavily it is loaded. The length of a ship may be from about 450 to more than 600 feet. Since the feasible range of detection for these targets was only slightly more than one nautical mile, the length of each ship at broadside aspect subtended more than the 3-degree horizontal extent of the beam, while the average height of each target was sufficient to fill only one-fourth or less of the vertical extent of the beam. As the equipment was scanned over the horizontal plane it was found that the signal indication was much stronger at two slightly separated orientations, evidently those at which the beam included either the fore or the aft superstructure, than at intermediate orientations for which neither white-painted superstructure was included in the beam.

Measurements of the range of detection were successfully made on eleven ships, using several combinations of flash-lamp source and photomultiplier detector tube. The shortest observed target range, set by the distance from the test station to the ship channel, was 5,200 feet. Even at this minimum feasible test distance it was not possible to detect a ship when the Polaroid XR3X44 filter was over the transmitter. The maximum observed range of detection with the Wratten 87 filter was 6,800 feet; with no filter, 7,500 feet. The increase in range obtained by removal of the filter is thought to have been limited principally by overloading of the photomultiplier tube due to radiation backscattered from the atmosphere, since a much greater increase in range would have been expected on the basis of the

ehT value of the filter, atmospheric attenuation and distance effects. However, other conditions of the tests could not be closely controlled. For example, it was not possible to identify each ship in order to determine its size, nor to tell whether or not it was heavily loaded with cargo. The changing aspect presented by the ships as they moved past the test station along the navigation channel constituted another variable factor not fully accounted for. The possible effects of ship lights on the noise level of the photomultipler tube, and of ship smoke on the ranges of detection, should also be considered. The importance of the latter effect is illustrated by the twice-observed fact that it was not possible to detect the more distant of two ships which passed each other almost directly off the test station, presumably because of the extra attenuation introduced by the smoke trail of the nearer ship.

`The visual range of the transmitter when covered with Polaroid XR3X44 filter was between 150 and 1,100 feet; with Wratten 87 filter it was considerably in excess of 1,100 feet. The project was terminated before an accurate threshold visual-range determination was made with either filter.

6.3.3 Discussion and Evaluation

The results of the detection tests on lake freighters were used as a basis for estimating the probable results on military vessels. The estimated range of detectability for a destroyer, using a Wratten 87 filter on the equipment, is about 7,000 feet. The effective operating range which might be secured by incorporating a number of possible refinements and using components of superior quality was thought to be about 2 nautical miles for a destroyer and 3 for a large battleship.

The possible effectiveness of using retrodirective reflectors of the highway-marker type as targets for this equipment was also considered. A battery of 12 such reflectors, each 3 inches in diameter, should give approximately twice the range of detection for a destroyer, or about 4 nautical miles. Installations of these reflectors would be particularly effective in making possible the detection of small ships and boats, marker buoys, etc. However, the only advantage of these reflectors over the high-precision Mt. Wilson triple mirrors, used as targets for the equipment described in Section 6.2, is their relatively low cost and ease of procurement. With the less precise reflectors of the highway-marker type the IRRAD equipment needed to provide equal operating ranges is heavier, bulkier, and probably more costly than would be justified by the difference in cost of the two types of reflectors.

The relatively short operating ranges indicated by the field tests described above, the low estimates based thereon for the range of detection of military vessels, and the low visual security afforded by the experimental apparatus when the Wratten 87 filter was used did not appear to warrant additional development, tests, and demonstrations. Bureau of Ships personnel concurred with NDRC representatives in the opinion that the limited ranges of successful operation which can be obtained with IRRAD equipment of reasonable weight and size do not have potentially significant military value. The project was therefore terminated without an official demonstration for the Armed Services. It is recommended that the future reopening of such a project be contingent upon the development of new and improved components which might offer the possibility of increasing the range of detection by an order of magnitude. In the absence of such new developments, further work on IRRAD systems should be confined to types designed for the detection of retrodirective reflectors of high accuracy, as described in Section 6.2.

Chapter 7

GLIDER POSITION INDICATOR AND CLOUD ATTENUATION METER

By *Thomas R. Kohler* [a]

7.1 INTRODUCTION

Early in the use of towed gliders as troop or matériel transports it became apparent that a blind-flying system, which would enable the glider pilot to maintain the correct position behind the tow plane, would be extremely useful. Accordingly, at the request of the Army Air Forces, such a system was developed at the University of Michigan under Contract NDCrc-185 as Project Control AC-56.

7.1.1 Analysis of the Problem

The Army Air Forces sought an infrared device for indicating, within ±2 degrees, the position of a glider with respect to its tow plane 400 feet away through clouds. This problem might be solved by a device which would indicate the position of the glider relative to the tow plane directly (a *positional* system), or by a device which would operate from the heading and flight attitude of the glider with respect to the tow plane (a *directional* system). With the directional system the glider might be in the proper position, but the device would indicate "out of position" if the glider were not pointing in the proper direction. Conversely, under this system it would be possible for the glider to be "out of position" and be indicated as "in position." A positional system, on the other hand, would enable the pilot to know at any instant the position of the glider with respect to its desired position regardless of its flight attitude. If the glider began to deviate from the desired position, this system would indicate directly the magnitude and direction of the deviation. The positional system seemed, therefore, to be the obvious and best solution to the problem. The *glider position indicator* [GPI] [1] is a true positional system.

[a] Department of Engineering Research, University of Michigan.

7.1.2 Atmospheric Attenuation

In any equipment such as this, the range of operability is critically dependent on the atmospheric attenuation to which the signal radiation is subjected between the transmitter and the receiver. Thus, if the transmitter at a fixed distance from the receiver would produce at the receiver an illumination E_0 with only clear air between, and an illumination E with a certain cloud between, the relation between these two values is:

$$E = E_0 e^{-kx},$$

where x is the distance between transmitter and receiver and k is the attenuation coefficient of the cloud. The decibels of attenuation would then be expressed as: $20kx \log_{10} e$ or $8.7kx$. The factor 20 is used, since it is the voltage rather than the power output of the receiver which is proportional to the radiant energy arriving at the receiver.

In the case of near infrared radiation, the attenuation coefficient is known to be very nearly the same as for visible light, but no data were available, in usable form, on the limiting values to be expected in dense clouds. For this reason a *cloud attenuation meter* [CAM] [2] was designed and built to investigate the values of the attenuation coefficient likely to be encountered in dense clouds. In this investigation, the information desired may be divided into three categories: (1) the cloud attenuation values existing between the transmitter and receiver of the glider position indicator at any given time; (2) the maximum cloud attenuation values which might be encountered; (3) a correlation between the cloud attenuation coefficient and the visual range. Item (1) would establish the performance characteristics of the GPI model actually constructed with reference to operation through clouds. Item (2) would establish how powerful the GPI would have to be in order to operate through any cloud condition that

might be encountered. Item (3), if such a correlation exists, would make possible the determination of the attenuation coefficient by a very simple measurement which could be made at almost any location with no auxiliary equipment, since the visual range is merely the limiting range at which a large dark object may be seen on the horizon. The relationship[3] between visual range and the attenuation coefficient is given by:

$$X_m = \frac{1}{k} \log_e \frac{1}{\varepsilon},$$

where

X_m = visual range,
k = attenuation coefficient,
ε = threshold contrast.

Values of ε computed by means of this equation, from experimentally determined simultaneous values of X_m and k, appear to indicate that ε is not constant under all conditions but may vary from 0.02 for visual ranges of several miles to 0.065 for visual ranges of approximately 100 feet.

While the CAM was originally designed specifically to measure the attenuation of near infrared radiation by dense clouds over short ranges, it could easily be adapted for general studies of the transmission of visible near infrared radiation by the atmosphere.

7.2 GLIDER POSITION INDICATOR

7.2.1 General Description and Mode of Operation

The GPI consists essentially of a near infrared transmitter, mounted on the tow plane, which scans a 20x20-degree field in which the glider is to fly, and a receiver, mounted in the nose of the glider, utilizing a photoconductive thallous sulfide cell as the radiation detector. The receiver circuits are synchronized with the transmitter scan by means of a cable along the tow rope in such a way as to indicate the glider's position in the field scanned by the transmitter.

As shown in Figure 1, the transmitter projects a narrow beam of radiation in the general direction of the glider. This radiation is given a compound oscillatory motion by means of two vibrating mirrors with sinusoidal motions at right angles. The result is a Lissajous figure of frequency ratio 6 to 1

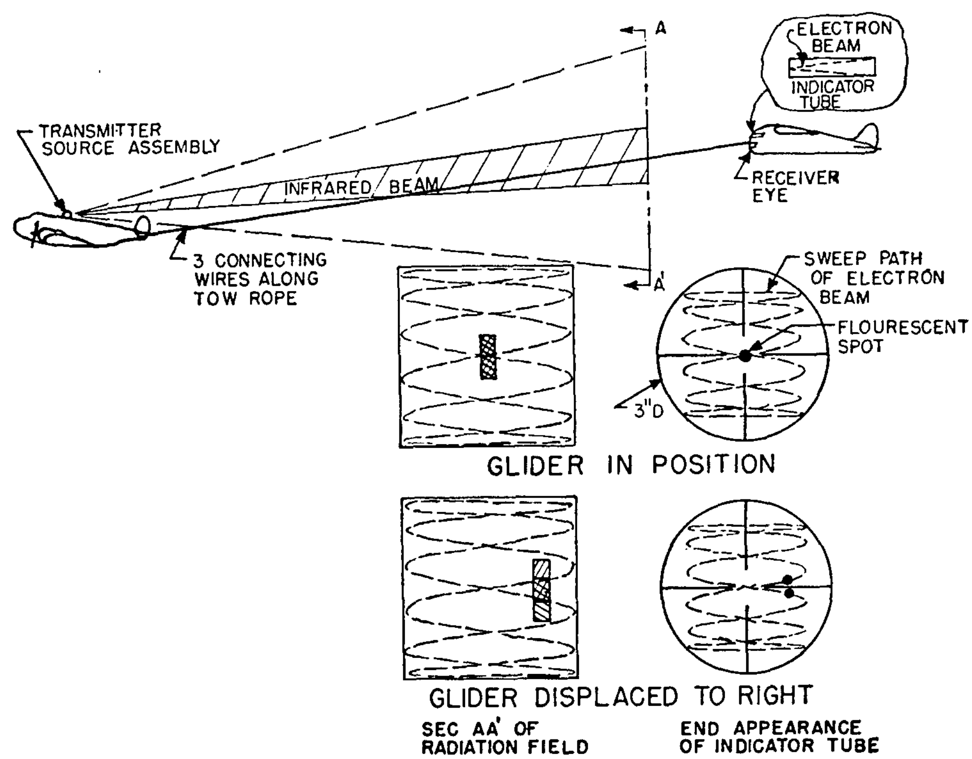


FIGURE 1. Operation of infrared glider position indicator.

in that the beam is swept across the field 6 times in the horizontal direction for each one in the vertical. The complete scanning process is repeated 14 times a second.

The glider pilot has before him a cathode-ray oscilloscope, the electron beam of which is driven exactly in synchronism with the scanning radiation beam from the transmitter. This is accomplished by means of electrical pickups at the transmitter mirrors which deliver the synchronizing voltages to the receiver through the cable along the tow rope. Thus the trace of the transmitted radiation beam

7.2.2 Description of Component Parts

TRANSMITTER

The optical system of the transmitter consists of a tungsten lamp, the radiation from which is focused by a 3-inch parabolic mirror of 2 inches focal length into a beam subtending 1 degree by 5 degrees. The beam is reflected from the first vibrating plane mirror to the second, and then to the zone in which the glider is to be located. The two vibrating mirrors impart to the beam the scanning motion de-

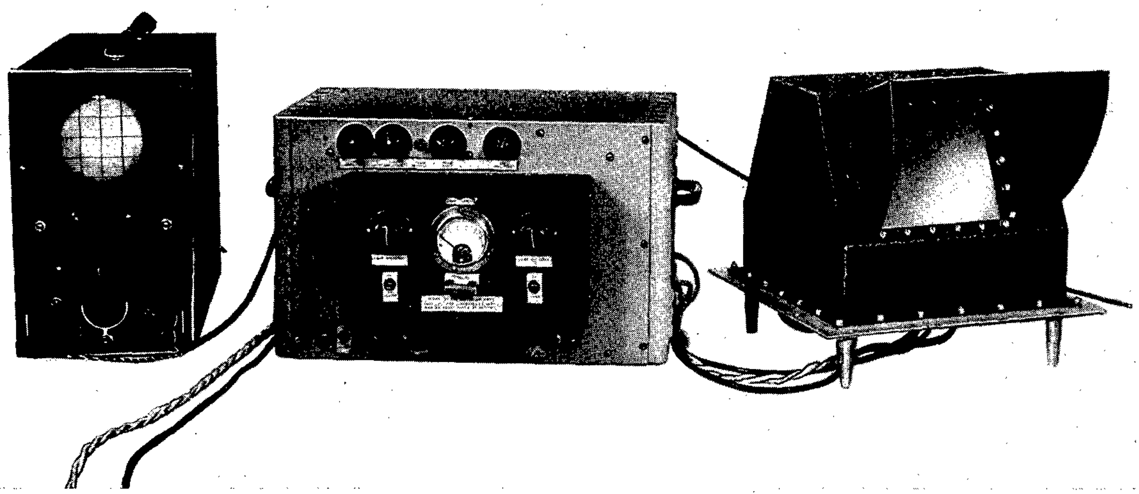


FIGURE 2. Components of the transmitter. Left to right: monitor oscilloscope, control cabinet, source-optical system.

on a vertical plane through the glider's nose and the trace of the electron beam on the screen of the cathode-ray oscilloscope describe similar patterns and remain exactly in step while doing so. However, the intensity of the trace on the screen is suppressed below the visual threshold, except at that moment when the transmitted radiation beam passes over the detector cell located in the nose of the glider. The electrical impulse from the cell is amplified and is made to energize or "trigger" the spot on the oscilloscope screen up to a visible level *at just this time,* so that the spot makes its appearance *at just that place* in the electron beam pattern on the screen which corresponds to the glider's position in the radiation beam pattern. This arrangement will be recognized as a rudimentary television system with the radiation pickup in the screen itself.

scribed in Section 7.2.1. The optical portion of the transmitter is 11x15x15½ inches and weighs 56 pounds. This size can not be greatly decreased without a corresponding sacrifice in size of the projected field. In addition, the transmitter includes a control cabinet, containing amplifiers for the mirror drives, and a monitor oscilloscope. Figure 2 shows the components of the transmitter, and Figure 3 is a block diagram showing the various amplifiers and phase-shift circuits of the transmitter. The total weight of the transmitter is 206 pounds. This weight could be considerably reduced, as the monitor oscilloscope probably would not be necessary and the control cabinet could be made considerably smaller and lighter than in the experimental model. The transmitter is operated from a 110-volt a-c and a 12-volt d-c supply.

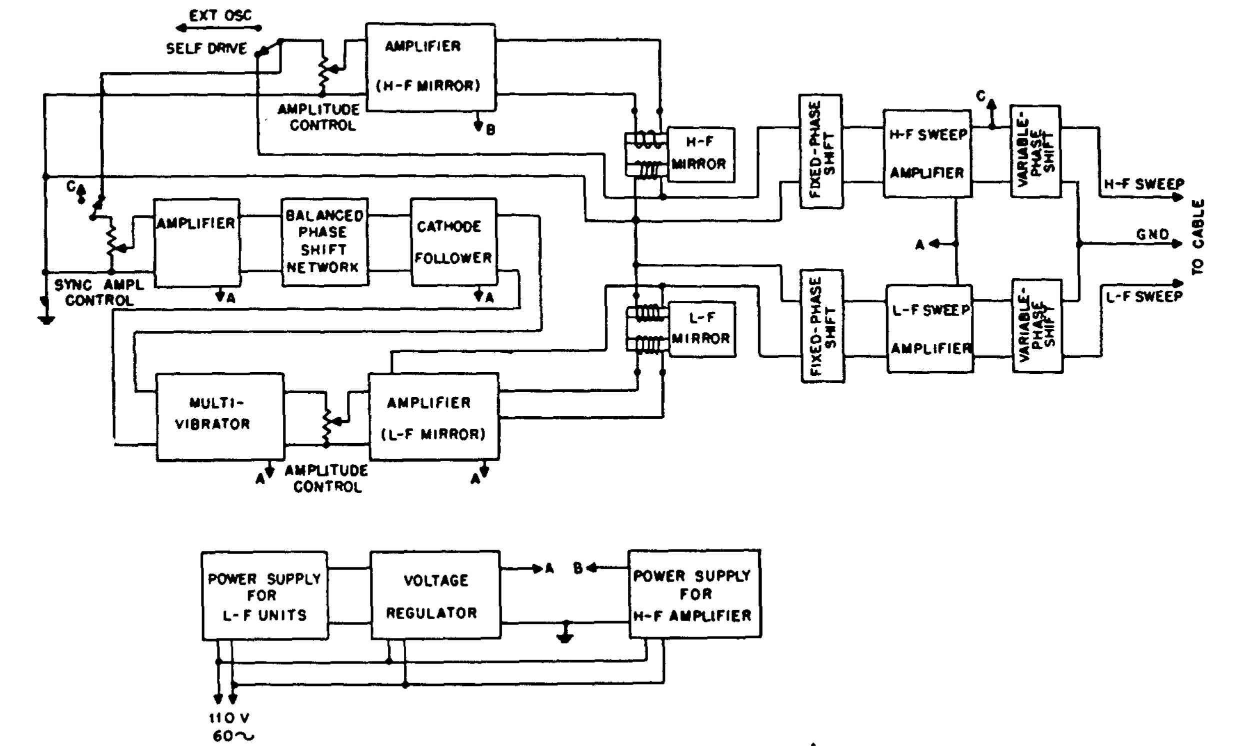


FIGURE 3. Block diagram of transmitter circuits.

RECEIVER

The optical "eye" of the receiver utilizes a spherical mirror to collect the radiation from the transmitter and to concentrate it on the radiation-sensitive thallous sulfide photoconductive cell. The combination of cell and mirror which was used gave a field of view subtending 20x20 degrees. The electric signal from the phototube passes through a preamplifier, an amplifier, and a differentiating circuit to a trigger circuit which controls the intensity of the spot on the cathode-ray tube. This sequence is indicated in the block diagram of the receiver shown in Figure 4. The cathode-ray oscilloscope cabinet also contains amplifiers for the sweep synchronizing voltages obtained from the transmitter through the connecting cable to the tow plane. The components of the receiver are shown in Figure 5.

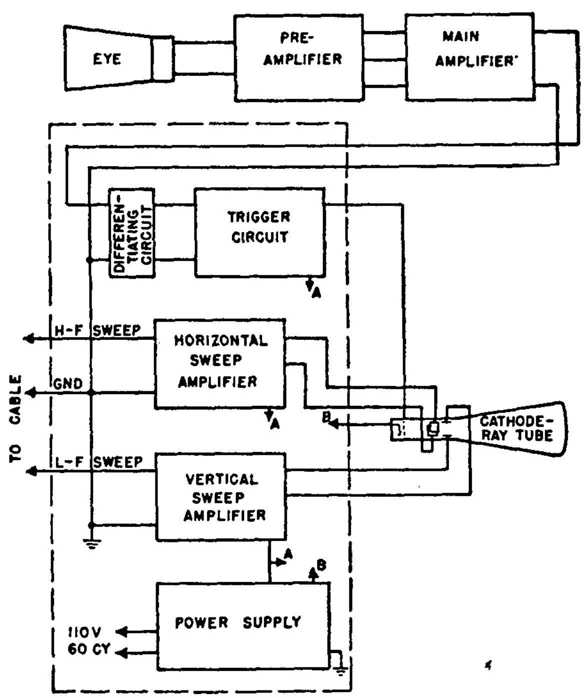


FIGURE 4. Block diagram of receiver circuits.

7.2.3 Operating Tests

GROUND TESTS

Preliminary tests were made in clear weather on the University of Michigan laboratory roof during July 1943 to determine the sensitivity of the equipment under both day and night conditions. It was determined that, with 200 feet separating the transmitter and receiver, the receiver response was approximately 45 db above threshold; that is, about

45 db of attenuation could be tolerated. The amount of tolerable attenuation showed no marked dependence on sky brightness, which varied from zero to 250 candles per square foot during these tests.

The GPI was tested during August 1943 on the summit of Mt. Washington, New Hampshire, where the effect of actual clouds on the operation of the equipment could be determined. The CAM was used to measure the cloud attenuation.

The GPI was found to be capable of penetrating 36 decibels of cloud under daylight conditions, with the transmitter and receiver 217 feet apart. Such a cloud would have an attenuation coefficient k of 1.9 per 100 feet. At night the GPI could penetrate about 45 db of cloud, or a cloud with an attenuation coefficient of 2.4 per 100 feet. These cloud attenuation values would be approximately equivalent to visual ranges of 144 feet and 114 feet, respectively.

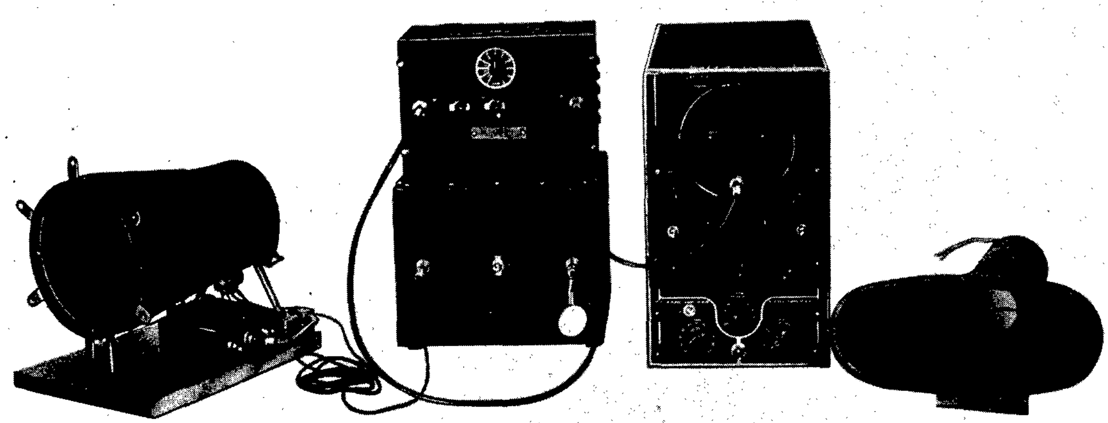


FIGURE 5. Components of the receiver. Left to right: detector-optical system (receiver eye); preamplifier (below) and amplifier (above); oscilloscope cabinet containing sweep amplifiers, trigger circuit, and power supply for cathode-ray tube; cathode-ray tube for signal presentation.

FLIGHT TESTS

The GPI was flight-tested at the Clinton County Army Air Base near Wilmington, Ohio, during November 1943. Because Army flight rules did not permit flight during those times when cloud conditions were thick enough for a stringent trial of the equipment, tests were made in clear air.

Four flight tests were conducted, at altitudes up to 10,000 feet. A standard tow rope (350 feet long) was used throughout the trials. The various glider pilots experienced no difficulty in maintaining the glider in its correct position by means of the indications from the GPI. The equipment operated satisfactorily without attention or adjustment. So far as it was possible to ascertain from observations and comments made by the pilots, the GPI possessed the essential operating characteristics originally requested. That is, it indicated the position of the glider at all times when the glider was in its assigned 20x20-degree field, with a horizontal resolving power considerably better than the minimum requirement of two degrees. It was somewhat deficient in vertical resolving power (2.5 degrees instead of the required 2.0 degrees). It must be noted, however, that the position indication spot blanked out during operation of the plane's radio, a circumstance which could perhaps be eliminated by additional shielding of the radio transmitter or the GPI receiving circuits (see Section 7.2.4). No change in performance with change in altitude was detected.

7.2.4 Discussion of Test Results and Recommendations

Experience gained during the various operating tests, together with the comments of the pilots, indicate the desirability of the following improvements, all of which appear to be feasible:

1. Increase the field scanned by the transmitter and the field of view of the receiver eye from 20x20 to 30x30 degrees.
2. Make the scanning pattern finer by increasing the number of horizontal sweeps per vertical sweep. This would increase the resolving power in the vertical direction.
3. Provide an indicator and manual controls or completely automatic controls for amplitudes of the vibrating mirrors in the transmitter, in order to maintain any required angular dimensions of the scanning field at all times.
4. Provide the shielding necessary to isolate the position-indicator circuits from the plane's radio.
5. Provide a control for aiming the transmitter in the vertical plane, adjustable in flight. This would permit adjustment of the equipment to allow for any desired change in the preferred glider position during an actual flight.
6. Make the position-indicating spot on the cathode-ray tube screen very much brighter.

The tests made through real and simulated clouds show that the GPI would be some 7 to 16 db deficient in penetrating power through the densest clouds, even at a separation of only 200 feet between glider and tow plane. This is assuming that flight is possible through clouds having an attenuation coefficient k of as much as 3.0 per 100 feet. The improvement demanded to achieve operation at 200 feet under these conditions is not beyond what might be achieved in an improved model, incorporating refinements over the first experimental model described here. However, to achieve operation at 400 feet through such clouds or at distances of 200 feet or more through very much denser clouds (if they exist under possible flight conditions) would require a penetrating power more than an order of magnitude better than the experimental model. This cannot be achieved by any method now apparent for equipment of this type. If and when the further development of such a system may be considered, the following questions will be crucial: (1) How short a tow rope may be contemplated. (2) What maximum cloud attenuation must be provided for.

The results of the flight tests in clear air indicate that, apart from cloud-penetrating power, the present model has the required essential operating characteristics. Another model could include the six recommendations previously outlined and, in addition, be made much lighter, more compact, and require less power. It does not appear feasible, however, to reduce materially the size of either the transmitter optical system or the receiver "eye," or to dispense with the three-wire cable along the tow rope in a system of this type.

7.2.5 Present Status

Although the field tests of the GPI showed that it possessed the general operating characteristics originally requested for military applications and the feasible modifications which would improve its practical usefulness were clearly outlined, the Army Air Forces at that time decided not to request any further development.

7.3 CLOUD ATTENUATION METER

7.3.1 General Description

The CAM consists of a *control-meter unit* [CMU] and a *reflector-modulator unit* [RMU] located at a chosen distance from a *source-detector unit* [SDU]. These are shown in Figure 6. In operation, as shown in Figure 7, the SDU projects a beam of radiation through the chosen optical path to the RMU, which retrodirectively reflects a portion of the beam to the detector in the SDU and at the same time modulates it at 90 cycles per second. The detector then measures, by means of a tuned amplifier and metering circuit, the returned radiation. Comparison of such a measurement made through a cloud with a measurement made through clear air allows one to compute a value for the attenuation coefficient k of the cloud. A means for standardizing readings has been included in the SDU in order to make an absolute calibration unnecessary each time the instrument is used.

7.3.2 Description of Component Parts

Source-Detector Unit

The radiation source is an 85-watt, 13-volt, tungsten flashing-signal lamp. Mounted coaxially behind

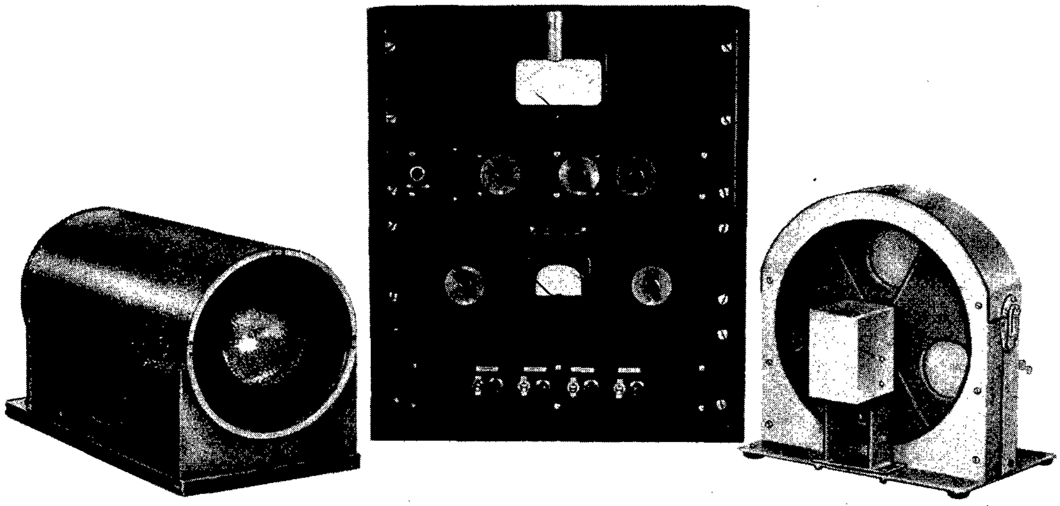


FIGURE 6. Cloud attenuation meter. Left to right: source-detector unit, control-meter unit, reflector-modulator unit.

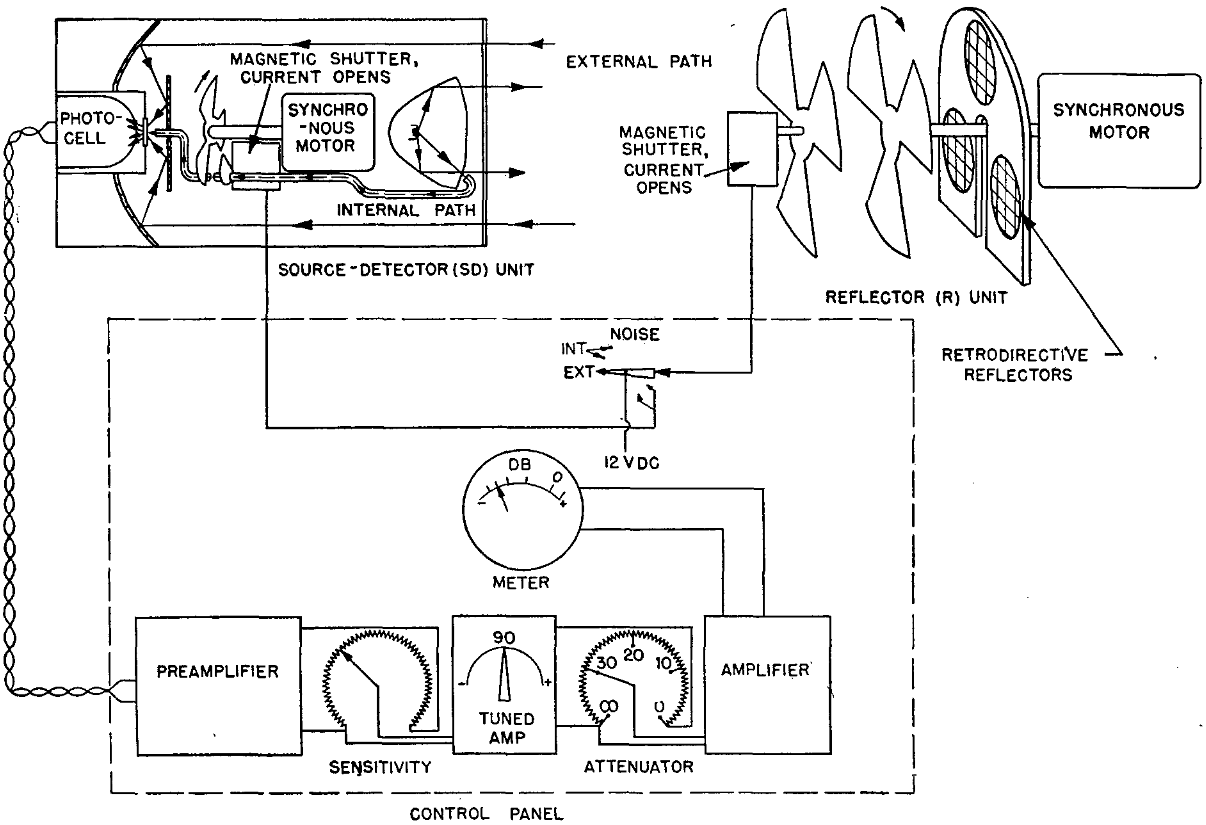


FIGURE 7. Schematic diagram of cloud attenuation meter.

the source is a parabolic mirror of 7⅝-inch aperture. The parts of an annular mirror which are not obscured by the parabolic one (see Figure 7) collect the radiation returned to the SDU by the RMU and directs it by means of an auxiliary plane mirror onto a diffusing glass screen behind which is mounted a thallous sulfide photoconductive cell. Also included in the SDU is an auxiliary light path consisting of three Lucite rod segments leading from the source to the detector. At the two spaces between these segments are inserted a motor-driven chopper for modulating the light and a magnetically controlled shutter. When the shutter is open, light is "conducted" from the lamp to the diffusing glass screen, being modulated in the process. Since the magnitude of this "internal signal" is independent of external atmospheric transmission conditions, it provides a reference signal to which all other reading may be referred in terms of decibel differences. This feature is considered especially important, as the "external" and "internal" readings are affected identically by changes in lamp characteristics, lamp voltage, photocell responsivity, amplifier gain, and unmodulated masking flux received either from daylight or by back reflection from the beam. With a thallous sulfide cell as the radiation detector a correction for the effect of masking flux is essential. For this purpose it is advantageous to use a cell selected to have the least possible dependence of responsivity to masking flux.

REFLECTOR-MODULATOR UNIT

This unit consists of a group of three retrodirective highway reflectors of standard commercial type centered at the corners of an equilateral triangle. A motor-driven modulator is mounted on an axis through the center of the triangle, its three blades successively covering and uncovering all three reflectors simultaneously. A shutter with three blades, mounted on the same axis and operated by an electromagnet, may be thrown into either the "open" or "closed" position by means of a switch on the CMU.

CONTROL-METER UNIT

This unit contains the amplifier and meter for measuring the output of the detector. The amplifier is a resistance-capacitance coupled type provided with a parallel-T negative feedback network for tuning it to 90 cycles per second, the modulation frequency. The gain of this amplifier is down 3 db at 87 and 93 cycles. The metering circuit is of the logarithmic vacuum-tube voltmeter type, so that the output meter reading is linear in decibels.

In addition, controls for the shutter, motor, and lamp in the SDU and for the shutter and motor in the RMU are incorporated. Thus all controls are centralized in this one unit which can be installed at any convenient location within a reasonable distance from either or both of the other two units.

7.3.3 Theory of Operation

To obtain the data required for computing the attenuation coefficient the shutters are operated in several ways. (1) With the shutter over the reflectors open and the shutter in the internal path through the Lucite rod closed, the meter will measure the intensity of the radiation received from the retrodirective reflectors. This is the "external" reading. (2) With the shutter over the reflectors closed and the Lucite path open, the meter will read the "internal" or reference signal. (3) With both shutters closed a reading of the noise level of the equipment, which sets a lower limit for obtaining valid signal readings, may be made.

In using the CAM, it is first necessary to obtain "clear" readings in the absence of appreciable attenuation in order to establish a reference level for the readings when fog or clouds are in the optical path between the SDU and RMU. The difference in decibels between the two readings is a direct measure of the amount of attenuation encountered over the entire path of the radiation from the source to the reflector and back to the detector. Since the "clear" and "cloud" readings may be separated by several hours, the necessity for the internal reference signal is apparent.

The loss of flux caused by the fog is given in terms of the attenuation coefficient by

$$\frac{I}{I_0} = e^{-2ky}$$

where I and I_0 are the amounts of reflected signal flux received by the detector through clear air and through fog, respectively, and y is the distance between the SDU and the reflectors. The attenuation caused by the fog is given in terms of decibels by

$$\begin{aligned} db_F &= 20 \log_{10} e^{-2ky} \\ &= 40 \log_{10} e^{-ky} \\ &= -17.4\, ky, \end{aligned}$$

in which I and I_0 are treated as voltages in the electrical circuit. The attenuation caused by the fog is given in terms of the meter readings by

$$db_F = (db_e - db_i) + (db_i^\circ - db_e^\circ),$$

where db_e = external fog reading,
db_i = internal fog reading,
db_e° = external clear reading,
db_i° = internal clear reading.

7.3.4 Field Test Results

In February 1943, a preliminary model of the CAM, designed to be installed in a PBY airplane, was taken to the Naval Air Factory in Philadelphia, Pennsylvania. Three weeks were spent at this time in making flights. No clouds suitable for measurement were encountered at times when the weather conditions permitted flights to be made. It was decided, therefore, that future tests would have to be conducted on the ground at places where clouds were present much of the time.

The CAM was set up temporarily at the summit of Mt. Washington in August 1943 when the GPI was tested there. Visual range measurements were made simultaneously with readings on the CAM. From the simultaneously measured values of the cloud attenuation coefficient and the visual range a probable value was obtained for ε, the threshold contract factor introduced in Section 7.1.2, of about 0.065. There was, however, quite a large spread above and below the figure in the individual values of ε computed from the experimental data. The maximum attenuation coefficient that occurred during these tests was found to be 2.9 per hundred feet.

In order to obtain more extensive data on the attenuation coefficients of clouds at visible and near-visible wavelengths, and also to obtain additional information on the relationship between the attenuation coefficient and visual range, arrangements were made to install the CAM in the Mt. Washington Observatory and to have frequent observations and readings made over a period of months.

In the data obtained from these tests, values of k up to 5.9 and of visual range down to 50 feet were observed. Whether or not these represent the limiting values which may be encountered in clouds is not definitely known, but it is certain that they will only infrequently be surpassed.

7.3.5 Discussion of Field Test Results

It is unfortunate that, because of the difficulties inherent in the measurement of atmospheric properties, the data obtained from the Mt. Washington installation are not entirely consistent and so do not lead to explicit and reliable numerical relations between visual range and the attenuation coefficient k. However, the data do show the following general characteristic trends.

1. The experimental values of the attenuation coefficient k show a considerable spread in relation to visual range, the discrepancies becoming quite serious at the greater visual ranges. This is generally to be expected, since the path of measurement extended somewhat less than 60 feet, and all but the shortest visual ranges had to be observed over a path distinctly different from that for which the attenuation was measured.

2. The correlation between the attenuation coefficient and the visual range apparently indicates a trend toward smaller values of ε for larger values of visual range. This is in accordance with the results of previous work,[4,5] but the trend occurs at smaller visual ranges and is of much greater degree than would be expected from the earlier results.

3. Although it had been hoped that the results would enable a choice to be made between the values of 0.02 and 0.065 for ε (cf. Section 7.1), the indications are for a value intermediate between 0.02 and 0.065 for visual ranges between 50 and 100 feet, and for a value less than 0.02 for visual ranges between 100 and 150 feet. The latter indication, in particular, is hardly plausible and indicates the need for obtaining additional data under carefully controlled conditions.

Sources of Error

The determination of uniform and valid corresponding values of visual range and attenuation coefficient is unavoidably beset by difficulties which lead to errors. Some of these sources of error are given below.

1. Differences between the path of instrumental measurement and the path of visual range observation, both with regard to length and location. When the cloud is nonuniform, and particularly

when there is considerable wind (as there invariably is on Mt. Washington), this is a possible source of error which becomes increasingly serious with increasing discrepancy in the length and location of the two paths. The steadiness or unsteadiness of the instrumental readings gives an index of this effect. Shielding by buildings and consistent vertical variations in cloud density would introduce systematic errors.

2. In the CAM itself, nonlinearity in response of the thallous sulfide cell could introduce a systematic error. Actually the response of thallous sulfide cells is known to be nonlinear at high signal levels, but this difficulty was minimized through careful selection of the cell. Experimental checks on linearity of response versus signal intensity indicated entirely satisfactory performance of the CAM in this respect.

3. Condensation of moisture on either or both of the windows covering the SDU and the RMU would lead to erroneously high values of the attenuation coefficient, k.

4. It is perhaps possible (though it seems unlikely) that some change occurred in the decibel calibration of the output meter circuit upon which the decibel difference readings depend. It had not been possible to obtain a check on this calibration at the date of the contractor's final report.

Conclusions and Recommendations

In view of the apparent discrepancies in the data, it does not seem possible to draw any definite conclusions with regard to either a maximum value for the attenuation coefficient of clouds found at the summit of Mt. Washington or a generally valid correlation of the measured values of the attenuation coefficients with the observed visual ranges. However, the data tend to support the existence of a trend in this correlation, in a direction such as to require for very short visual ranges a higher contrast between test object and surroundings than the classical value of 0.02.

In order to obtain really satisfactory simultaneous data on the attenuation coefficient and the visual range, the paths used for the attenuation measurement and the visual observation should be identical. This requirement is of course difficult, if not impossible, to meet exactly, but in future experimental work every effort should be made to approximate it as closely as possible.

7.3.6 Present Status

At the conclusion of the experimental measurements on Mt. Washington, the CAM was transferred to the Army Engineer Board, Ft. Belvoir, Virginia, for use in further investigations of the transmission characteristics of the atmosphere for near infrared radiation. It is anticipated that more complete information on these characteristics will continue to be of considerable interest and value in relation to actual or contemplated military equipments utilizing radiation in this wavelength region.

Chapter 8

FAR INFRARED DETECTING ELEMENTS

By *Harald H. Nielsen* [a] and *Alvin H. Nielsen* [b]

8.1 INTRODUCTION

All bodies which are at temperatures above absolute zero emit heat radiation which is entirely similar to ordinary light except that the wavelengths are much longer. These radiations are called infrared and are generally taken to embrace the wavelengths from 0.8 to about 400 μ, where 1 μ is 10^{-4} centimeter. Radiation of this kind cannot be seen, and beyond 1.5 μ cannot even be photographed. For its detection, heat-sensitive devices must consequently be relied upon.

For a body in equilibrium with radiation (a so-called black body), the wavelength at which the emission is a maximum is inversely proportional to the absolute temperature. For such a body, the maximum intensity of emission at that wavelength

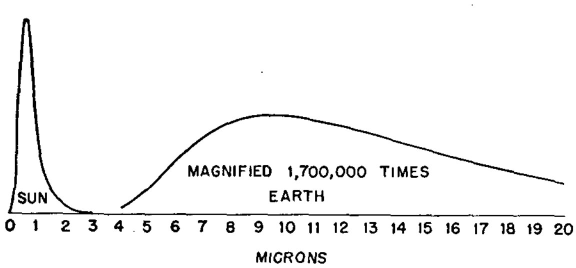


Figure 1. Computed black-body energy curves for two bodies of equal size, one at 6000 K (Sun), the other at 287 K (Earth).

is proportional to the fifth power of the absolute temperature. For example: the wavelength at which the emission of the sun (6000 K) is a maximum lies in the visible region (at about 0.5 μ); while, at room temperatures, the maximum emission of a black body is at a wavelength some 19 times greater (9.5 μ), and lies in the far infrared. The intensity of emission or surface brightness for the sun at 0.5 μ is approximately three million times (19^5) greater than it is for a black body at 27 C near its maximum of emission. This is shown in Figure 1.[1] The emission for a black body as a function of wavelength is given by Planck's equation. This equation is plotted in Figure 2 for the temperatures 50 C, 0 C, and —50 C.

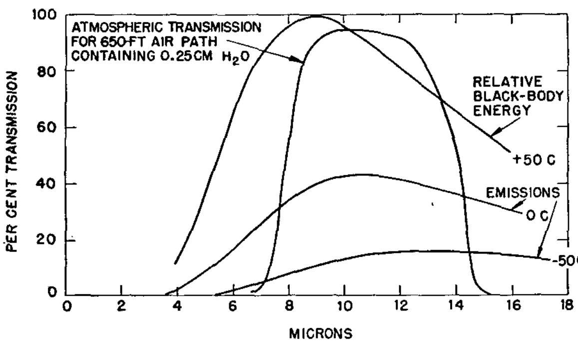


Figure 2. Atmospheric transmission curves for air path containing 0.25 cm precipitable H_2O.

Whereas the total radiation of a black body integrated over all wavelengths is proportional to the fourth power of absolute temperature, the spectral emission at ordinary temperatures, integrated from 8.5 μ to 13.5 μ, is approximately proportional to the fifth power of the absolute temperature. This is because emission at the black-body maximum is proportional to the fifth power of the absolute temperature, and the emission at the wavelengths from 8.5 μ to 13.5 μ lies near this maximum at ordinary temperatures.

The approximation is expressed analytically as follows:

$$B = \int_{8.5\,\mu}^{13.5\,\mu} J_{\lambda T} d\lambda \simeq AT^5 = 1.9 \times 10^{-9} T^5, \quad (1)$$

where B represents the far infrared brightness (in microwatts per square centimeter per steradian; B is the emission of a black body at T degrees absolute, integrated throughout the far infrared wavelength band 8.5 μ to 13.5 μ.

The military value of infrared detectors for observing the movements of ships offshore and the massing of military equipment and personnel in the

[a] Mendenhall Laboratory of Physics, Ohio State University, Columbus, Ohio.
[b] Department of Physics, University of Tennessee, Knoxville, Tennessee.

field suggests itself immediately, and indeed a very considerable effort has been expended to develop heat-sensitive devices for purposes of this kind. Objects of the greatest interest from a military standpoint are generally at temperatures only slightly above those of the background and almost always below the boiling point of water. On the assumption that such objects as are of military interest may be regarded as *black* (i.e., objects which completely absorb and emit all wavelengths of radiation), a simple calculation shows that the preponderance of the radiation transferred to a black-body receiver lies in the wavelength interval 5 μ to 15 μ.

Throughout the spectrum from 0.8 μ to the very long wavelengths, there exist regions of absorption due to molecules in the atmosphere. At these points the atmosphere is frequently almost opaque to infrared radiation, hence it is a fortunate circumstance that there exists an atmospheric transmission window just in the region from 8.5 μ to 13.5 μ. Figure 2 shows the observed transmission of the atmosphere for an optical path of 650 feet, with 0.25 cm of precipitable water vapor present.

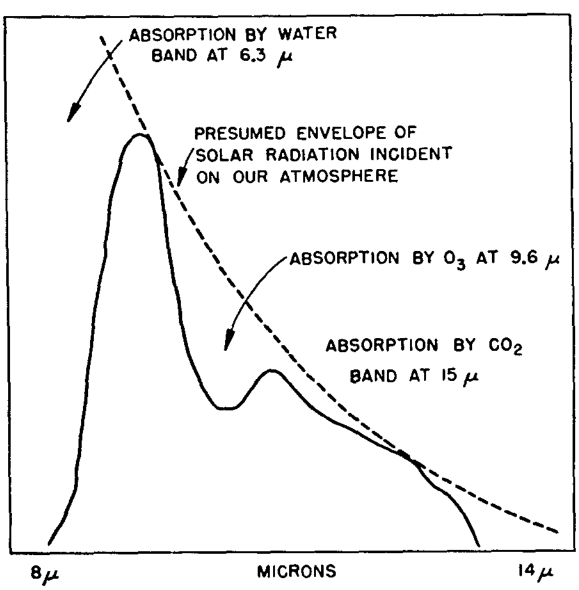


FIGURE 3. Solar energy transmitted by the Langley window.

This transmission curve depicts the so-called "window" in the atmosphere, discovered by Langley and first defined by Fowler's measurements as reproduced in Figure 3.

Figure 4 shows a graph of the transmission, as deduced from solar observations, using the 8.9-μ residual ray band of quartz. The transmission is plotted against the amount of water vapor in the solar beam, and it may be presumed to be repre-

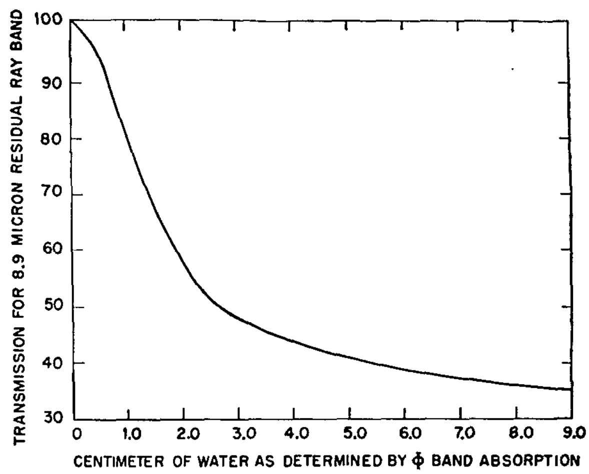


FIGURE 4. Centimeter of water as determined by Φ-band absorption.

sentative of the transmission of the whole 8.5-μ to 13.5-μ band. The heat-sensitive devices must, therefore, function for radiations in this wavelength interval.

The developments have been of widely varying natures, but in every case the responsivity of the device has been related to the temperature change developed in the receiving element of the detector by the incident radiation. The great variety in the types of detectors which have been developed and built makes it very desirable that comparative studies be made to obtain as much information as possible about their relative merits, i.e., their responsivities, response times, noise output, equivalent noise input, minimum detectable signal, etc. At the joint request of the Army and the Navy, Contract OEMsr-1168 was set up at the Ohio State University, as Project Control AN-6, under the auspices of Section 16.4 of NDRC, to make comparative tests on the various American thermal detectors. In addition, tests on captured enemy thermal detectors were officially requested as Project Control SC-127.

This chapter summarizes the work done on the development of far infrared detectors under Contracts OEMsr-126 and OEMsr-1147 at Massachusetts Institute of Technology, under Contract OEMsr-60 at Harvard University, and under Contract OEMsr-636 at Bell Telephone Laboratories,

also the testing of these detectors under Contract OEMsr–1168 at the Ohio State University. The detectors developed by the above-named contractors are the Harris evaporated thermopile, the Strong nickel-strip bolometer, and the Bell Telephone Laboratories thermistor bolometer, respectively. Construction details and other data of a physical nature obtained from the final reports on these contracts, as well as performance data from OEMsr–1168, are included in subsequent sections. Brief paragraphs on the performance of other far infrared detectors, developed outside Section 16.4 but tested under this section's auspices, are also included in order that a comparison may be made of a wider variety of types.

8.2 TYPES OF DETECTORS

The several kinds of heat-sensitive units which have been developed fall essentially into three groups; namely, thermopile units, bolometer units, and the Golay cell.

8.2.1 Thermopiles

A thermocouple consists of two junctions between different kinds of metal, for example bismuth and antimony, and operates on the principle that when one junction suffers a temperature change relative to the other a thermoelectric voltage is developed. The magnitude of the electromotive force developed depends on the nature of the materials used, i.e., the thermoelectric powers, the dimensions and heat capacity of the element, and the blackness of the rectangular receivers affixed to the junctions. A thermopile is essentially a series of thermocouples, usually joined in series, but sometimes in parallel.

Five thermocouples were submitted to Contract OEMsr–1168 for testing. Of these, the Harris evaporated thermopile was the only Section 16.4 development; the others, obtained from commercial sources, were the Weyrich, Schwarz and two types of Eppley thermocouples. One of the latter was used with the Emerson detector and the other with the Farrand device.

8.2.2 Bolometers

A bolometer is made of a material which has a high temperature coefficient of resistance, either positive or negative. When the strip of material is exposed to heat radiation, its temperature will increase with an accompanying change in resistance. If the bolometer is incorporated in an electric network, the current flowing through it will be altered as the bolometer resistance varies. A measurement of the changes in currents in such an electric network can be utilized to determine the amount of thermal power falling on the bolometer strip.

Eight different detecting units of the bolometer type were examined under Contract OEMsr–1168. Two of these, Bell Telephone Laboratories [BTL] and Radio Corporation of America [RCA] bolometers, were found to have negative temperature coefficients of resistance. (This type will hereafter be referred to as the thermistor bolometer.) Five of the remaining six units, the Strong nickel-strip, the Felix, the Polaroid, an Italian bolometer, and the German Donau Gerät are essentially of the metal-strip type. The sixth, the Andrews device, contains a strip of columbium nitride which becomes superconducting near the triple point of hydrogen. The BTL bolometer is distinctly a high-impedance device; the RCA bolometer is of intermediate impedance, and the rest must be regarded as low-impedance instruments.

8.2.3 The Golay Heat Cell

The Golay heat cell, or photothermal unit, operates on the principle that a pressure-volume (p-v) change occurs in a gas when its temperature is increased or decreased. The unit consists essentially of a metal chamber which contains the gas. The front of the chamber is closed by a membrane which acts as a receiving element, and the back is closed by a distensible mirror membrane. When radiant heat falls on the receiver, the temperature of the gas within rises, and the accompanying pressure increase causes the mirror to distend. Light from a small lamp is made parallel and passed through a grid of parallel lines and focused on the mirror by means of a meniscus lens placed near the mirror. The mirror in its undistended shape causes an image of the grid to be formed in the plane of the grid so that the grid-bar images and the real grid spaces coincide, thus permitting virtually no light to reach a photocell, the function of which is to transfer the p-v change into an electric impulse. When the mirror is distended by the increase in pressure, the image of the grid is focused in a

plane other than that of the grid so that light may now be passed by the combination to the photocell. This device provides a great deal of optical amplification. The changes in photocell current may then be further amplified by electronic means.

8.3 GENERAL CONSIDERATIONS

8.3.1 Methods of Specifying the Responsivity of Detectors

To specify the responsivity of heat detectors, a number of things must be taken into consideration. If a detector having a receiving area A (square centimeters) is in a radiation field of flux density F (watts per square centimeter), its responsivity may in general be given alternatively in terms of its output per unit of flux density (watts per square centimeter) or in terms of its output per unit of flux (watts). The latter may be obtained from the former by dividing by A. The various detectors operate on different principles and, therefore, the output may be specified in different ways. In this chapter the responsivity defined in terms of volts per watt has been used exclusively.

In the case of the thermopile, radiation falls on one set of junctions and an emf results, which can be measured by means of a galvanometer. The responsivity might, therefore, be thought of as the ratio of the electromotive force generated to the temperature change developed between the *hot* and *cold* junctions. Since this change is directly related to the power incident on the receiver, the responsivity might also be regarded as the ratio of the thermal emf produced to the power (say in microwatts) falling on the thermocouple.

When radiation falls on a bolometer through which a current is flowing, the change in the bolometer's resistance is recorded in the potential drop across its terminals. This may be measured by means of the voltmeter. If there is a ballast resistance in series with the bolometer, the responsivity can be specified in two ways: (1) in terms of emf per watt of incident power under specified operating conditions, as in the case of the thermopile; or (2) in terms of the fractional change in resistance ($\Delta R/R$) per watt of incident power. These remarks apply both to the high- and low-impedance types of bolometers.

The Golay cell, however, being a pressure-volume device, does not directly generate a voltage as the result of the absorption of heat radiation, and a different definition must be employed. To be sure, the unit has an auxiliary optical amplification system in conjunction with the heat cell which operates a photocell circuit so that the incident power does establish a voltage, but this system is incidental to the heat cell. The responsivity of the heat cell alone could probably best be given in terms of the fractional pressure change, $\Delta p/p$, per watt of incident power.

On the basis of numbers representing the responsivity alone, difficulties would be encountered in comparing the performance of the detectors with each other. Because of this difficulty and because each type of unit has a different amount of noise associated with it, a different method of comparing them must be used. A method which measured the signal detected together with the noise was consequently chosen as the criterion.

8.3.2 Noise Considerations

The output from a thermal detector must, in general, be amplified in some manner before the response is sufficiently large to be recorded or indicated in some other manner. This may be accomplished, for example, by the successive cascade of amplification stages which will allow a small signal to be built up to any desired size. It might appear reasonable that the thermal detector which will produce a usable output with the smallest amount of amplification would be the best detector to use. This, however, is not necessarily true, since a device which may be regarded as an extremely sensitive detector, and, therefore, may operate with small amplification, may have an inherent noise which is more than proportionately large. An inherently very quiet, but insensitive detector with a high-gain amplifier may be able to detect smaller heat signals than an inherently noisy, but highly sensitive detector with a low-gain amplifier. The excellence of a detector is its ability to detect a signal and to distinguish it from the inherent noise of the system.

The noise at the output-indicating mechanism where the signal response is viewed will consist of the noise originating in the thermal detector plus noises originating in the amplifier. In the region viewed or scanned by the detector there may, of course, exist thermal fluctuations in the background in addition to those which it is desired to

detect. Target fluctuations of this sort which tend to obscure the signal are not considered in this chapter. The noise originating in the detector and in the amplifier cannot be completely eliminated by any design of the system. These limiting noises are inherent in the nature of the detecting system.

LIMITS OF USEFULNESS BECAUSE OF NOISE

The nature of the inherent noises in a detecting element cannot here be discussed in detail. They may, however, be visualized in somewhat the following manner. Consider a mirror suspended by a fiber in a medium of gas particles. Assume, moreover, that a light beam is reflected by the mirror and is focused at a point so as to produce a trace on a moving photographic film. If the mirror were clamped rigidly, the trace would be a straight (noiseless) line on the photographic film.

The gas particles are, however, constantly executing random motions (Brownian motions), the magnitudes of which are related to the absolute temperature of the gas. This random motion is communicated to the suspended mirror by collisions of the particles with the mirror. The mirror will, therefore, suffer random fluctuations from its zero position and the trace on the photographic film will no longer be a straight line but will contain zigzag deviations. The lack of definition produced in this manner is indicative of the *Brownian noise* present.

It might appear in the foregoing naïve example that the effect could be minimized or even reduced to zero by pumping away the gas. It is, of course, clear on second thought that the random motions of the gas particles are not the only random motions present. There will also be the random motions of the atoms in the fiber, random motions of the atoms where the fiber is supported, and so forth. This is consistent with the analysis, as it rests entirely on statistical laws and does not depend on the mechanism of the energy fluctuations.

In electrical phenomena it is the velocities of the electrons themselves which fluctuate randomly. In a vacuum tube these random motions give rise to the *shot effect* (statistical fluctuations in the rate of emission of electrons), and in an electrical circuit they manifest themselves as the *Johnson noise* (fluctuations in the voltage across an impedance element).

In addition to the Johnson noise originating in the thermal detecting elements, there may be other noises such as microphonic or current noises. During tests made under Contract OEMsr-1168 very little microphonic difficulty was encountered with any of the detecting elements studied. This was not entirely true of these devices when used in the field. Current noise is a voltage fluctuation across a resistor, the existence and magnitude of which depends upon the current passing through the resistor. When the current passing through the resistor is zero, the current noise is zero. Current noise is predominantly a low-frequency phenomenon and the noise voltage components decrease rapidly with increasing frequency. Since a bolometer is a detecting device which may carry a considerable current through it when operating, current noise may become significant. In tests made on certain devices, current noise was quite evident.

The Johnson noise is the form of thermal agitation which is of principal interest, since it sets a lower limit on the least detectable signal. The Johnson noise measured across a resistor will depend upon the temperature of the resistor, the magnitude of the resistance, and the width of the frequency band in which the noise is measured. The mean square noise voltage due to thermal agitation, $\overline{v^2}$, integrated over all components between the frequencies f_1 and f_2, may be shown to be

$$\overline{v^2} = 4kTR(f_2 - f_1), \tag{2}$$

k being the Boltzmann constant, T the absolute temperature, and R the resistance. At a temperature of 290 K, (2) becomes

$$\overline{v^2} = 1.59 \times 10^{-20} R\ (f_2 - f_1)\ \text{volt}^2. \tag{3}$$

After amplification by an amplifier of gain G_f, the voltage available for measurement will be

$$\begin{aligned}\overline{v^2} &= 1.59 \times 10^{-20} R \int_0^\infty G_f^2 df \\ &= 1.59 \times 10^{-20} R \Delta f G_M,\end{aligned} \tag{4}$$

where Δf denotes the effective noise bandwidth, G_M the maximum value of G_f, and R is presumed to be a constant over the frequency bands for which G_f is large. A measuring system of conventional design will contain a band-pass amplifier over a single band of frequencies with a maximum gain G_M within this band and a zero gain outside. The effective noise bandwidth may then be evaluated

from a knowledge of the experimental gain data and the relation

$$\Delta f \equiv \frac{\int_0^{\infty} G_f^2 df}{G_M^2}. \tag{5}$$

The effective noise bandwidth for the amplifiers used in the experiments on which this report is based was obtained in this manner.

Estimation of Expected Noise

It is possible that the lower noise limit set by the Johnson noise of the detecting element may never be reached because of noise which may originate in the amplifying system. These amplifier noises which add to the noise of the detecting element itself may be of the following kinds.

1. Johnson noise and current noise in the amplifier parts, particularly in those parts associated with the input bridge circuit.
2. Shot noise fluctuations in the space-charge-limited vacuum-tube currents, caused by the random emission of the electrons.
3. The flicker effect caused by changes in the surface conditions of the emitter (confined to low-audio and sub-audio frequencies).
4. Microphonics associated with mechanical vibration of the charged units, tube electrodes, and faulty contacts.

It has been the experience of those working under Contract OEMsr-1168 that the total output noise was invariably larger than the Johnson noise to be expected from the input circuit. For this reason an extrapolation from the amplifier noise to the expected Johnson noise has been made in all cases in order to evaluate the performance of the detector. In this manner, the lowest limit of usefulness of the device has been estimated. In this report there will be found, therefore, not only the best results which it was possible to obtain under Contract OEMsr-1168,[2] but also the best results which might be expected if a perfect amplifier were used with the detector, and if the only noise originating in the detector were Johnson noise.

The noise in the output can all be reduced by limiting the bandwidth of response of the output indicating mechanism. When sufficient time is available for the detection of a signal, a slowly responding indicator may be used. This use implies that the effective frequency pass band Δf becomes narrower, and, in effect, averages out some of the noise. Thus, for example, an observer watching the fluctuating needle of an instrument for a period of time would automatically apply an averaging process and thereby, through elimination of some of the component frequencies, reduce the effect of the noise in obscuring the signal. If, on the other hand, only a short interval is available for the detection and perception of a signal, a rapidly responding instrument must be used, and as a result the effective frequency pass band is widened. A more rapid method of detection is inherently accompanied by a larger amount of noise than is a slow method of detection.

8.3.3 The Equivalent Noise Input

It has been indicated earlier that the real merit of a detector is reflected in its ability to distinguish a signal from the noise. This quality has been made the basis for a comparison among the various detectors studied. The actual quantity which has been determined in each case is known as the *equivalent noise input* [ENI] and represents the amount of signal input necessary to produce an output equivalent to the noise. A more explicit definition of the ENI follows.

$$\text{ENI} = \lim_{\substack{\text{signal in}\to 0\\ \text{signal out}\to 0}} \frac{\text{(rms noise voltage output)}}{\dfrac{\text{(rms signal voltage out)}}{\text{(signal input)}}}, \tag{6}$$

where rms is used as an abbreviation for root mean square. The denominator is the limiting value of the responsivity for very small signals. When the amplification is linear over the entire range of noise and signal levels, the limiting process is unnecessary. The input signal has been measured in peak-to-peak microwatts for all values in this report.

The ENI was obtained in actual tests by plotting the output from the amplifier against the heat signal applied to the thermal element. Whenever the output of the amplifier was proportional to the input, the ENI could be obtained by extrapolating the curve to zero and noting for what value of the input the ordinate has the same value as the output noise, the latter being read when a shutter was interposed between the detector and the heat source. This is illustrated in Figure 5.

It has already been pointed out that the output noise observed was greater than the Johnson noise

which one might expect from the thermal element alone. The ENI becomes, in reality, an indication of the sensitivity, since the more sensitive units will give the smallest ENI for a given output noise level. The reasons for this are believed to be intimately related to the fact that the amplifier must be tuned to frequencies in the low-audio range in order that the thermal elements themselves may operate effectively. At these frequencies the flicker noise in the first stage of amplification may be sufficient to exceed the Johnson noise. For this reason a *minimum equivalent noise input* [MENI] has consistently been determined also. The MENI is the heat signal computed to be necessary to produce an rms voltage output equal to the rms Johnson noise voltage of the thermal detector alone. This would be the ENI expected if a noiseless amplifier and bridge circuit could be built and if the thermal detector had no other noises than Johnson noise.

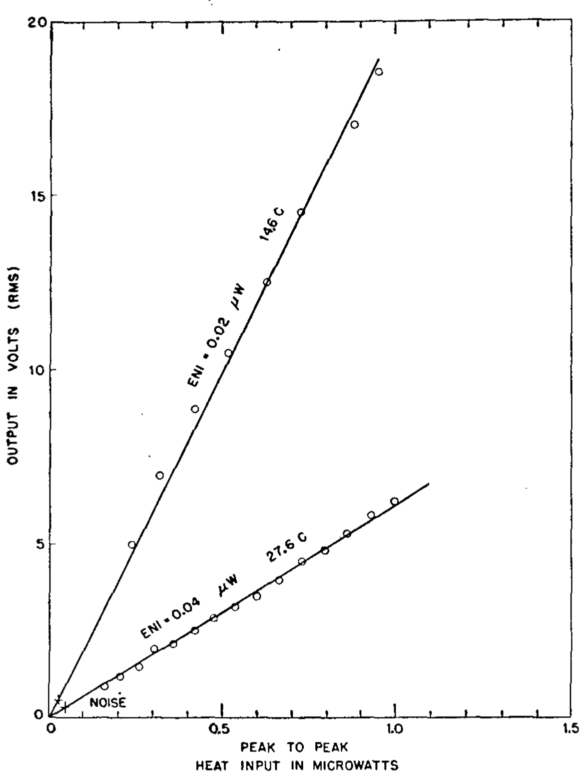


FIGURE 5. Heat test on Felix bolometer with black body and tuned amplifier.

The units in which the ENI and MENI are given are the same as those in which the input signal is measured, microwatts, ergs per second, etc. In the determination of these quantities the peak-to-peak value of the square-wave-heat power incident upon the thermal element has consistently been employed. This represents the magnitude of the d-c power available for detection before it is chopped into a square wave.

The ENI and the MENI will both depend, as has already been suggested, on the pass band of the amplifier. In general, the same tuned amplifier was used on all the thermal detectors studied, except the BTL bolometer, so that the pass-band width has been the same in virtually all the comparative tests made under Contract OEMsr–1168.

8.3.4 The Minimum Detectable Signal

Another indication of the merit of a thermal detector is the *minimum detectable signal* [MDS]. This been been regarded as an estimate of the magnitude of a signal required to produce a response on an Esterline-Angus recording milliammeter which can just be definitely seen above the noise. This quantity was evaluated by recording the output from the tuned amplifier on the Esterline-Angus meter while signals were impressed on the thermal elements at intermittent intervals, a record of the magnitude of the signal being made each time. From these records an estimate was made of the least signal which could definitely be distinguished from the noise with a signal exposure time of about 30 seconds. This is illustrated in Figures 6 to 11 inclusive.

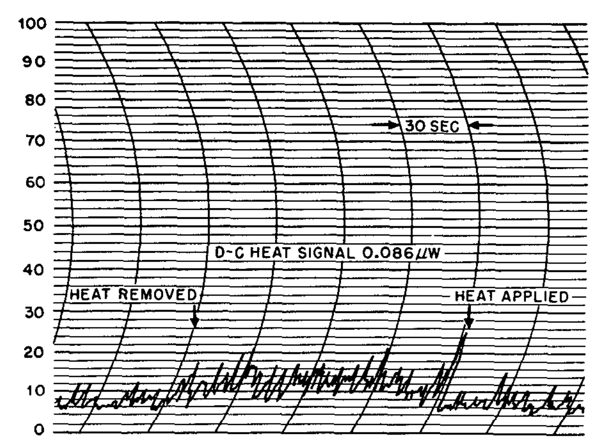


FIGURE 6. Determination of minimum detectable signal for Strong bolometer at 27.6 c tuned amplifier.

It is evident that neither the ENI nor the MDS can be accurately measured, since they are both

obtained from measurements relative to a noise background. They must, therefore, be as difficult to define and determine accurately as the noise itself. While the absolute value of the noise is not readily

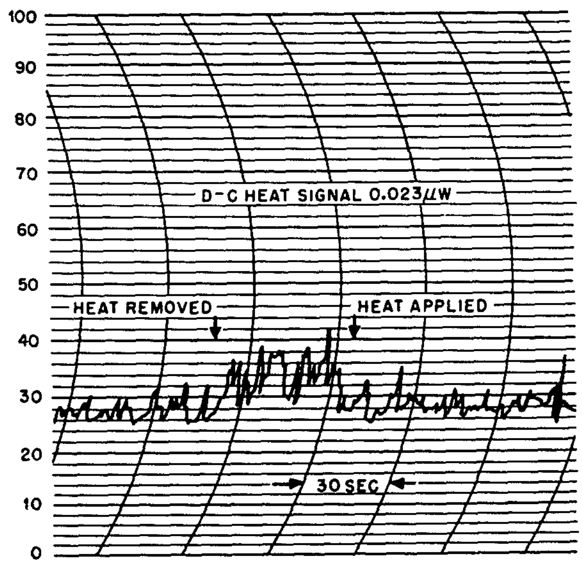


FIGURE 7. Determination of minimum detectable signal for Felix bolometer No. 19 at 27.6 c tuned amplifier.

estimated or metered when a narrow pass band system is used, measurements of the above type do allow a comparison of the relative merit, at least in certain specific characteristics, of the several units studied.

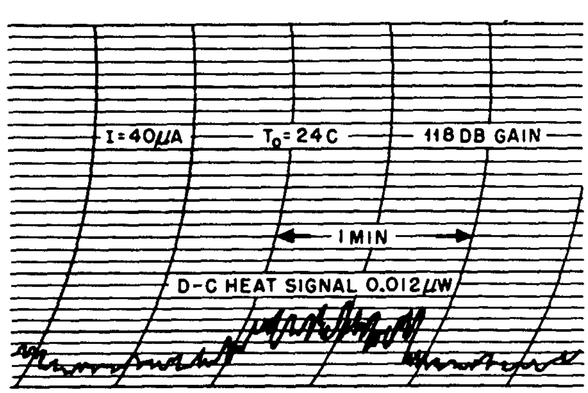


FIGURE 8. Determination of minimum detectable signal for BTL Becker bolometer No. 19 at 15 c.

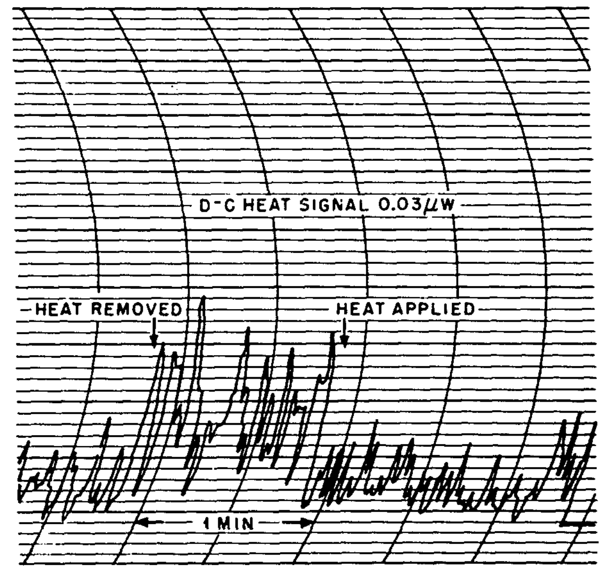


FIGURE 9. Determination of minimum detectable signal for RCA bolometer No. AX at 14.6 c.

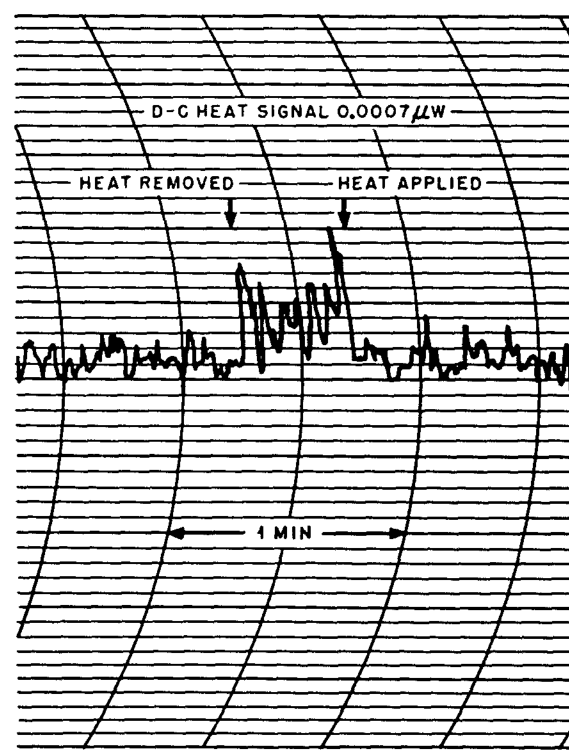


FIGURE 10. Determination of minimum detectable signal for superconducting bolometer No. 4 at 27.6 c.

Under Contract OEMsr-1168, a considerable number of devices were found to have ENI measurements which differed from each other by not more than a factor of two. When this is so it becomes quite difficult to attain a valid judgment of the merit of a device on the basis of noise measurements alone. In such instances, other factors, such as frequency response, compactness, and ruggedness, must be regarded as the differentiating characteristics.

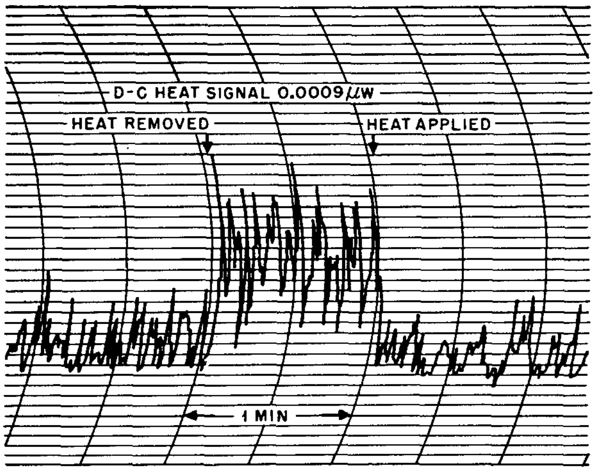


FIGURE 11. Determination of minimum detectable signal for superconducting bolometer No. 1 at 27.6 c.

8.3.5 Output of Thermopiles Predicted from the d-c Responsivity

When radiation of an amount dH (watts), effective in causing a temperature rise, falls on a thermal junction for a time long enough to produce an equilibrium between the heat power absorbed and the heat power lost, a thermal emf dV is generated. If there are n junctions in series, the voltage developed is ndV. The *responsivity*, $S_{d\text{-}c}$, in volts per watt of uninterrupted incident radiation, may then be expressed as

$$S_{d\text{-}c} = n\frac{dV}{dH} \text{ volts per watt.} \tag{7}$$

This expression can be made equivalent to equation (3) of reference 3,

$$\frac{V_{d\text{-}c}}{G} = \frac{nm}{L},$$

where $V_{d\text{-}c}$ = the voltage response to steady-state radiation,
n = the number of *hot* junctions,
m = the volts per degree for each junction,
G = the heat power absorbed by the thermopile in watts per square centimeter,
L = the heat power lost by the thermopile per degree rise in temperature in watts per square centimeter if each term is divided by the area.

If, however, the radiation is interrupted at a definite frequency so that the radiation does not fall on the thermopile long enough to establish equilibrium, the voltage generated per watt is not given by $S_{d\text{-}c}$, but by the smaller number

$$S_{d\text{-}c}\phi W, \tag{8}$$

where

$$\phi = \frac{\text{response at frequency } f}{\text{response at zero frequency}} \tag{9}$$

obtained from the frequency-response curve, and W = waveform factor, to take account of the manner in which the heat power is interrupted. The voltage at the output of an amplifier of gain G_f per watt of heat power input on the thermopile could, therefore, be expressed by the following relation:

$$\frac{dV}{dH} = G_f(S_{d\text{-}c})\phi W \text{ volts per watt.} \tag{10}$$

8.3.6 Output of Bolometers Predicted from the Static Characteristics

When radiation of an amount dH is permitted to fall on a bolometer strip of resistance R_b carrying a constant current I_b, the strip suffers a temperature change ΔT and, consequently, a resistance change ΔR_b. As a result, the potential difference across the bolometer will change by an amount which is $I_b\Delta R_b$.

FREQUENCY FACTOR ϕ

If the radiation is interrupted periodically so that the time of illumination is short in comparison with that required for the establishment of temperature equilibrium, the voltage change will be somewhat smaller than for uninterrupted illumination. The resistance fluctuations, and hence the voltage fluctuations, depend critically on the frequency of interruption of the illumination. This effect is clearly shown by the frequency-response curves, in which the response is seen to decrease as the frequency rises from the zero value. The zero-frequency voltage change across a bolometer for a heat power input of one watt could, therefore, be expressed by $I_b(dR_b/dH)$.

To obtain the voltage change at any other frequency, a multiplicative factor, which is the ratio of the response at the particular frequency to the response at zero frequency, must be applied. This factor may be obtained from the frequency-response curve.

WAVEFORM FACTOR W

In addition, the waveform factor W must be introduced, the value of which depends on the manner in which the heat power is applied and the output is measured. If the heat power input on the bolometer is a square wave measured peak to peak, and the bolometer output is fed into a tuned amplifier which passes only the fundamental component and this output is measured in rms volts, then W is 0.45. If the heat input is a sinusoidal wave measured peak to peak and the output is measured in rms volts, W is 0.35.

GENERAL RESPONSE EQUATION

When this voltage change is fed into an amplifier, the gain of which is G_f at the frequency of operation, the voltage output per watt of heat power input may, in general, be stated as follows:

$$\frac{dE_{\text{out}}}{dH_{\text{in}}} = G_f I_b \frac{dR_b}{dH_{\text{in}}} \phi W. \tag{11}$$

Where direct measurement of (dR_b/dH) is not possible, variations of this relation may be used to predict the voltage output. Thus, from the amplifier characteristics and the static characteristics, the bolometer output for any frequency may be computed. For the bolometers tested, the outputs have been computed and compared with the measured output. In general, the agreement has been good.

CIRCUIT DEPENDENCE AND BRIDGE FACTOR F

In a bolometer circuit the bolometer current I_b may not be a constant when the bolometer resistance is varied. The bolometer voltage change produced by a change in the bolometer resistance is not just $I_b \Delta R_b$, as presumed in the foregoing discussion, but $\Delta(I_b R_b)$. The change in bolometer voltage depends upon ΔI_b as well as ΔR_b and will, therefore, depend upon the circuit in which the bolometer is placed. The expression $G_f I_b \Delta R_b$, however, is the output voltage from the bolometer network, which may or may not contain transformers and vacuum tubes, if G_f is given the proper value. This value of G_f is the change in the output voltage in the network produced by the introduction of a 1-volt, zero-impedance source in series with the bolometer, all other circuit elements remaining the same.

In the case of the thermistor bolometers, which do not use a transformer to couple to the amplifier, the *bridge factor* of the bolometer network has been used. This bridge factor F is the G_f defined above but is applied only to the network which furnishes electrical power to the bolometer and from which the signal is taken for amplification.

8.3.7 Frequency Response of the Detectors

When modulated heat signals are received by infrared detectors, the response of the detector varies in some manner depending on the frequency of modulation of the signal. For bolometers, this problem has been studied in great detail, by a number of authors,[4] with respect to the various factors affecting the response, such as the thermal capacity of the element and its heat dissipation through radiation and conduction. In general, the response of the Golay cell fails at low as well as at high frequencies, and for this unit there exists a frequency of maximum response. Some units have the characteristic that when they are illuminated by radiant energy, the heating curve approaches a steady-state value exponentially. Similarly, when the radiation is shut off, the cooling curve falls off exponentially from the steady-state value to zero. Such heating and cooling curves are shown in Figure 35. The frequency behavior of such units is characterized by a time constant τ, which is the time required by the unit to reach a value on the heating curve of $(1 - 1/e)$ times its steady-state value (or to fall to a value in the cooling curve of $(1/e)$ times the steady-state value). For such units the voltage response to sinusoidally interrupted radiation may be given by the relation

$$V_{\text{out}} = \frac{V_{zf}}{(1 + \omega^2\tau^2)^{1/2}}, \tag{12}$$

where V_{out} is the response in volts, V_{zf} is the response at zero frequency, $\omega = 2\pi f$, and τ is the time constant in seconds. The time constant τ may also be given as the ratio of the effective heat capacity H of the bolometer to the total heat dissipation constant C, $\tau = H/C$. At low frequencies of modulation, $\omega^2\tau^2$ is small compared with unity and the response is independent of the frequency. At high frequencies the $\omega^2\tau^2$ term is large compared with unity and the response is proportional to $1/f$. On a logarithmic plot the response approaches these two situations asymptotically, and at the frequency f_0,

where these asymptotes intersect, the response is down 3 db from the zero-frequency asymptote. At this frequency, $\omega\tau = 1$ and the time constant $\tau = 1/(2\pi f_0)$.

If τ is small, then the response is not affected by as low frequencies as it is if τ is large. For a given element, if the heat dissipation can be increased, the time constant can be reduced with the same effect as is achieved by reducing thermal capacity. The result of this is to make a flatter response over a larger frequency interval. Various devices have been used, such as the introduction of gases and cooling plates to increase the heat dissipation. These devices in some cases alter the shape of the response curve so that the unit no longer behaves as if it had a true time constant and the high-frequency behavior may approach $1/\sqrt{f}$ rather than $1/f$.

It was the practice in the tests made under Contract OEMsr-1168 to make a frequency-response curve using a sinusoidal heat input of constant maximum amplitude and to measure the output at enough frequencies to determine both the low- and high-frequency behavior. The output in decibels was plotted against log frequency. The decibel numbers given on the frequency response are not the same for any two curves and are not related to the actual responsivity of the element. From the experimental response curve, it is then possible to determine whether the unit has a true time constant. If the response curve does not have the proper form, no time constant is reported, but the response can be read from the curve. In the case where no time constant exists, a substantial error might be made if an *effective time constant* were to be stated. The performance of some of the bolometers tested can be approximated by sensitivity and time constants over limited frequency ranges. The use of such time-constant data leads to erroneous results if applied outside the proper frequency range and may be radically in error if extrapolated to zero frequency (see Section 8.7.3).

The various detectors tested were designed to operate under widely different conditions. The BTL insulator-backed bolometer and the Schwarz and Harris thermopiles were designed to operate at atmospheric pressure, while the Strong and Felix bolometers were made to operate at reduced pressures in hydrogen gas. Some of the BTL bolometers were backed with various materials such as quartz, glass, rock salt, and plastic, while others were unbacked. The fact that few of the tested detectors had simple time constants was doubtlessly related in some manner to these design factors.

8.3.8 Spectral Characteristics of the Detectors

As the infrared detectors sent to Ohio State University for testing were of widely different design and materials, it was considered of interest and importance to investigate their response to radiation of different wavelengths. The detecting elements of the receivers were, in general, blacked with some material such as platinum, gold, or aluminum black. The detectors designed to operate at reduced pressure were equipped with a window through which the radiation must pass. Those operating at atmospheric pressure also required windows to eliminate acoustical pressure effects and moisture condensation on the elements.

The window materials used were silver chloride on the Strong, Felix, and RCA bolometers; rock salt on the Italian bolometer, the Harris thermopile, the Golay heat cell, and the Andrews cryostat; potassium bromide on the Weyrich thermocouple; gilsonite or silver sulfide coated rock salt and silver chloride on the BTL thermistors; fluorite on the Schwarz thermocouples; and thallous bromide-thallous iodide mixture on the Donau Gerät bolometer. Both blacking and window material affect the response as a function of the wavelength of the radiation. Because of the necessity for the use of a window, it was not possible to isolate window effect and blacking effect absolutely, though a fairly good guess could be made. In the case of the Strong bolometer, the coated silver chloride window was removed and a polished rock salt window was put on instead, with the result that the response was increased by a factor of two. In the case of the Felix unit No. 2A, the silver chloride window was exposed to sunlight with the effect that the 1-μ to 4-μ response was appreciably lessened without reducing the response throughout the remainder of the region by more than about 20 per cent.

Definition and Measurement of Absorptivity

The *spectral response* from 1 μ to 14 μ for each device was obtained by using the detector to receive radiation from a Nernst glower dispersed through a small Hilger rock salt prism spectrometer. The re-

sponse of each detector was compared with the response of a Coblentz thermopile throughout the same region, and the ratio of the detector response to the Coblentz response was plotted against wavelength. The Coblentz thermopile was considered to be uniformly black over the entire range.

In the case of the thermopiles, the ratio of the responses was set equal to unity at 2.0 μ, while for the bolometers this ratio was made to equal a quantity called the *absorptivity*, $a_2\mu$, defined as the ratio of the resistance change per watt of heat power input to the resistance change per watt of electrical power input $(dR/dH)/(dR/dP)$.

The quantity a_λ obviously depends on the wavelength of the radiation, because it really is a measure of the fraction of the incident heat power which is effective in causing a resistance change, and this fraction depends on characteristics varying with wavelength, such as the blackness of the receiver and the transmission of the window material.

The absorptivity was determined by the following method: The bolometer resistance was measured with a Wheatstone bridge, the voltage supply being varied. Thus, it became possible to plot a graph of R_b versus P (electrical power expended in the bolometer), as shown, for example, in Figure 12, from which dR/dP could be obtained. The term dR/dH was obtained by one of two methods.

Static Method. The term dR/dH was obtained by direct measurement of ΔR for a certain amount of heat power ΔH incident on the bolometer as follows: Radiation from a Nernst glower, which is principally 2-μ radiation, was focused directly on the bolometer strip, while the resulting ΔR was measured by a potentiometer method. ΔH was measured at the same time by means of the calibrated Coblentz thermopile. The ratio $(dR/dH)_{2\mu}$ could then be calculated and the ratio of $(dR/dH)_{2\mu}$ to dR/dP, obtained from the R versus P curve, is the absorptivity a_λ for λ principally 2 μ.

Dynamic Method. The term dR/dH was also obtained by a method which utilizes equation (11). Radiation from the Nernst glower was again focused directly on the bolometer strip and interrupted sinusoidally at 20 cycles. The voltage developed by the bolometer was fed into the primary of a transformer by means of a bridge circuit and the voltage at the secondary was measured by a Ballantine electronic voltmeter. I_b, the current through the bolometer, was measured with a calibrated voltmeter and shunt. ΔH was measured peak to peak by the calibrated Coblentz thermopile method. With the frequency response of the device available, all quantities in equation (11) are known with the exception of dR/dH, which can then be calculated. The transformer gain at 20 cycles was measured using an input circuit equivalent to the bolometer input.

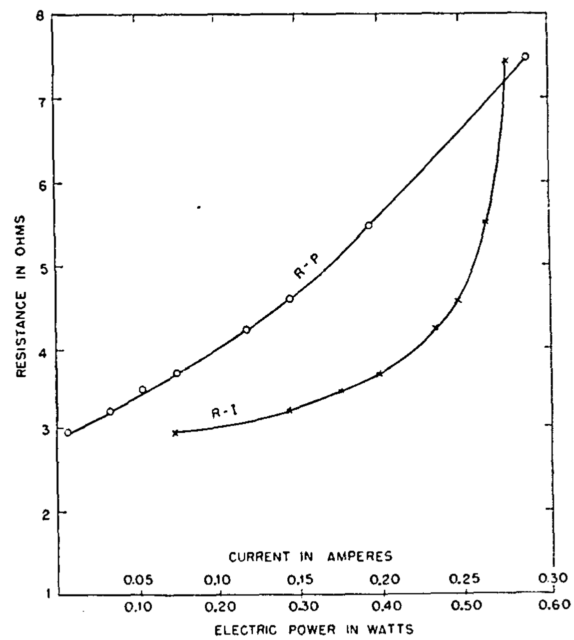


FIGURE 12. Static curves for Strong bolometer.

8.4 TEST EQUIPMENT AND METHODS DEVELOPED UNDER CONTRACT OEMsr-1168

Those working under Contract OEMsr-1168 were concerned with the comparative testing of various infrared detectors. Because a large part of the data on the detectors was obtained under that contract, the test methods developed under it are discussed here.

To facilitate the accurate measurement of small amounts of heat power, certain pieces of test equipment were constructed and certain more or less standard testing procedures were developed. The equipment was designed to be adaptable to a variety of detecting devices, so that a transfer from one device to another could readily be made. The equipment constructed and used in nearly all the tests, as well as the methods developed, will be discussed in the following paragraphs. Special testing equip-

ment equivalent to that which is discussed in this chapter was developed by BTL and is discussed in memoranda issued by that laboratory.[5,6]

HEAT SOURCES

As a radiation standard, a calibrated incandescent tungsten lamp was obtained from the National Bureau of Standards. Other sources used in the tests were calibrated against this lamp. The calibrating equipment comprised a Coblentz thermopile and a high-sensitivity Leeds and Northrup galvanometer. The thermopile, galvanometer, and a small resistance were connected in series. A thermal emf, generated by the known radiation flux of the standard lamp, caused the galvanometer to deflect. A known potential difference was introduced into the same circuit by passing a current through the small resistance with no radiation on the thermopile, and the galvanometer deflection was again read. From these deflections, and from the known radiation flux density and impressed emf, the responsivity of the Coblentz thermopile in volts generated per watt per square centimeter of radiation flux density was determined. Radiation flux densities from other sources than the standard lamp could then be measured rather easily.

The principal secondary radiation source used in most of the tests was a small low-temperature black body. This was a small brass cylinder about 1 inch in diameter and about 4 inches in length, with a conical cavity turned in the front end. The cavity was coated with lamp black. An electric heating coil, operated from a 6.3-volt transformer, was inside the cylinder and raised the temperature to about 115 C.

The black body was mounted behind an insulating board with a circular hole. A metal shutter, backed with insulating board, was inserted between the black body and the hole. The Coblentz thermopile, situated 30 cm in front of the emitting hole, viewed the hole and insulating board background. The temperature difference seen was, therefore, that between shutter and black body. This temperature difference was obtained by means of a pair of copper-constantan thermal junctions, the hot one imbedded in the black body and the cold one attached to the metal shutter which, because of the backing, remained at room temperature. The range of temperature differences was about 0 to 90 C.

The Coblentz thermopile was used to determine the flux density in microwatts per square centimeter for the various temperature differences as the black body cooled down to room temperature. A plot of these points agrees very well with the plot of flux densities versus temperature differences as obtained from Stefan's law,

$$F = 1.69 \times 10^{-12} A \frac{T_1^4 - T_0^4}{r^2} \text{ watts per sq cm},$$

where F is flux density in watts per square centimeter, A is the area of the shield hole, T_1 and T_0 are the absolute temperatures of source and receiver, respectively, and r is the distance between the shield and the receiver.

In the various tests performed on the heat detectors, one of a variety of shields was affixed to the emitting hole to limit its size and shape. To provide a square-wave heat input, a rotating sector wheel was located between the black body and the hole, and a rectangular opening was used on the emitting hole, the hole width being much smaller than each of the sector arcs. For a sinusoidal heat input, a wheel with a sinusoidal periphery was turned in front of a slit opening. Another method was to use a sector wheel and a hole cut in the shape of one half of a sine wave, the base of which is just the width of the sector in the wheel.

The temperature of the black body was varied between 20 and about 115 C, so that the radiation transferred to the receiver was chiefly in the 5-μ to 14-μ spectral region. In some of the tests performed, e.g., the frequency response and spectral response, it was more convenient to use a hotter source or one for which the radiation was peaked in the near infrared so that it contained a considerable amount of visible light. The Nernst glower was a natural choice because of its size and ease of operation. It is a rather narrow cylindrical source, constructed of a material with a negative temperature coefficient of resistance and made to operate in air. Its radiation peak is normally at about 2 μ and it is a fairly close approximation to a black body in this region. It deviates appreciably from black-body characteristics beyond 4 μ. This source is particularly convenient for frequency-response measurements because a visible small image of the source can easily be focused on the detecting element by means of a mirror. Because it is a narrow elongated source, a sinusoidal heat signal can rather easily be obtained by having a sinusoidal wheel interrupt the radiation from it. The flux density was

obtained as usual by the Coblentz thermopile. In the measurements of the spectral response of the detectors with the rock-salt prism spectrometer, the Nernst glower was a convenient source of infrared radiation because of its slitlike shape and because it radiates a great deal of heat energy.

Amplifiers

The amplifiers used in the tests were of two types, sharply tuned and wide band. For the frequency-response measurements of the various devices, a wide band-pass amplifier was experimentally determined so that the frequency-response curves for the various devices could be obtained. The low-frequency response was tested by means of an a-c voltage output from a photocell which received light of sinusoidally varying intensity. The frequency of the light variation was controlled by a sector wheel arrangement. Some heat-response measurements were also made with this amplifier.

Most of the heat measurements, from which the ENI were determined, were made with tuned amplifiers of which two were available. One of these, for 15 cycles, was supplied by BTL under Contract OEMsr-636 for use with thermistor bolometers designed by that laboratory and is described in one memorandum.[7] For the low-impedance bolometer, a tuned amplifier modified from specifications supplied by Harvard University Contract OEMsr-60 was used. The tuned output stages were separated from the input stage so that several types of input stages can be used with these or with the wide-band amplifier. This amplifier employs a Thordarson T-48094 input transformer which can be matched with the various units.

Several sets of twin-T circuits were built to be plugged into the amplifier, making operation possible at 14.6, 27.6, 47, 80, and 140 cycles. These circuits were quite sharply tuned, the noise band-pass being about 3 cycles for all frequencies except 14.6, for which it was 0.6 cycle. The twin-T networks had to be carefully adjusted for proper operation.

For each operation the gain was measured with a circuit equivalent to that of the bolometer. A Hewlett-Packard oscillator furnished the signal for these measurements and both input and output voltages were measured with Ballantine electronic voltmeters.

The heat-response measurements were made with a square-wave heat input measured peak to peak. The tuned amplifiers pass only the fundamental sinusoidal component of the square-wave input, and the output voltmeter reads the rms value of this component.

Frequency Response

To determine the frequency response of the various detectors a more or less standard procedure was followed, although it was necessary to vary the procedure slightly from case to case. The detector was irradiated by a sinusoidal heat input, the wheel interrupting the radiation beam being driven by a Cenco variable-speed rotator. The wheel used has already been described under "Heat Sources," Section 8.4. By this method frequencies from 1 to 300 cycles were produced.

When frequencies greater than 300 cycles were required, the black-body source was used with an opening in the shape of one half of a sine wave. A wheel with many sectors was used to chop the radiation, the width of the sector being the same as the base of the sine opening. The wheel was driven by a high-speed motor, and frequencies up to 2,000 cycles were thereby made available.

The output of the detector was amplified through the wide band-pass amplifier the frequency response of which was known over the entire range. This is described in the preceding section, "Amplifiers." During the frequency-response measurements on any detector the heat input was maintained constant.

If the frequency-response curve indicated that the thermal detector had a time constant, the *parallelogram method* was also used in certain cases. In this method, radiation chopped into square waves is permitted to fall on the detector. The detector output voltage is amplified without distortion of the wave shape and applied to one pair of oscilloscope deflection plates. The amplified output is also differentiated electrically and applied to the other pair of plates. The pattern which appears on the screen is a parallelogram. The slope of the proper sides of the parallelogram is proportional to the time constant of the thermal detector. A proportionality factor may readily be adjusted by setting the relative gains of the vertical and horizontal amplifiers on the oscilloscope. Even if the thermal detector does not have a time constant, the oscilloscope figure may still look enough like a parallelogram to give the impression that a time constant exists. The method

is, therefore, merely supplemental to the frequency-response curve method.

SPECTRAL RESPONSE

As the detectors tested were of various degrees of blackness and were fitted with windows of various materials, such as rock salt, fluorite, and silver chloride (coated and uncoated) in various states of transparency, it was considered of value to determine their response to radiation of various wavelengths. This response was obtained from 1 μ to 14 μ for the detectors and compared with the response of a Coblentz thermopile over the same range under similar conditions.

For these measurements, a small Hilger rock-salt prism spectrometer of Wadsworth design was used in conjunction with a Nernst glower. A sector wheel was used between the source and the first spectrometer slit to interrupt the radiation. The energy from the exit slit of the spectrometer was focused on the detecting element by means of a short-focus mirror. The spectrometer was calibrated to read wavelengths in microns after being adjusted to some known spectral line. The absorption by CO_2 at 4.25 μ was used as the standardizing line, and the absorptions by water vapor at 2.7 μ and 6.2 μ were used as further checks on the calibration. The slit widths used for the detectors were the same as those used for the Coblentz thermopile, so that a fair comparison could be made between the various detectors with the Coblentz as a standard.

The output of the detectors was fed to a tuned amplifier, and the amplified output voltage was read on a Ballantine electronic voltmeter. A curve was plotted for each detector in which the ordinate was the ratio of the detector's response to the Coblentz response and the abscissa wavelength in microns. This ratio was adjusted to $a_{2\mu}$ at 2.0 μ and is proportional to the absorptivity. In some cases, $a_{2\mu}$ was not known, so the curves were adjusted to unity at 2.0 μ.

MINIMUM DETECTABLE SIGNAL

A rectifier was built to operate an Esterline-Angus recording milliammeter from the output of the various amplifiers. With this device, it was possible to register both signal and noise on the same record. The Esterline-Angus recorder was also adapted to drive the prism table of the spectrometer in order to permit the use of the various detectors in recording spectra.

The detectors were set up to view the black body and the outputs were recorded on the milliammeter. As the black body cooled to room temperature, the shutter was held open for about one-half minute at regular intervals. The signal was thus recorded above the noise. The last signal clearly discernible above the noise was taken to be the MDS. Curves for the various detectors are shown in Figures 6 to 11, inclusive.

8.5 THERMOPILES DEVELOPED IN SECTION 16.4

8.5.1 The Harris Evaporated Thermopile

In order to obtain a radiation thermopile with a quick response, the metals composing the junctions must be exceedingly thin. The previously reported [8,9] sputtered and evaporated thermopiles have comparatively fast responses. A quite different design of *evaporated* thermopile [4] appears to be capable of somewhat greater responsivity, and the new *folded* thermopiles which were developed from these previous studies have a much faster response than conventional thermopiles. They compare favorably with other fast-responding infrared detectors.

According to the original proposals, rapid response was to be attained by permitting a high rate of heat loss, still using thin deposits of metal on a thin backing support. The overall responsivity was to be maintained by crowding many junctions into a small area. This was to be accomplished by evaporating metals about 1.5×10^{-4} centimeter thick onto folded strips of the insulating support material, with the hot junction at the fold and the cold junction just behind or below the hot junction. Figure 13 shows the structure of the thermopiles. The method of manufacture is fully described elsewhere.[3]

CONSTRUCTION DETAILS

Method of Evaporating the Metals. Previous studies [10] had shown that the resistivities of evaporated bismuth and evaporated antimony were 10 to 30 times as great as those of the massive metal. The new design would be impractical unless these resistivities could be appreciably reduced, as it is important that the thermopile resistance be low. Accordingly, the first task was to develop methods

for evaporating the metals so that the metal deposits obtained would have resistivities approaching those of the massive metals.

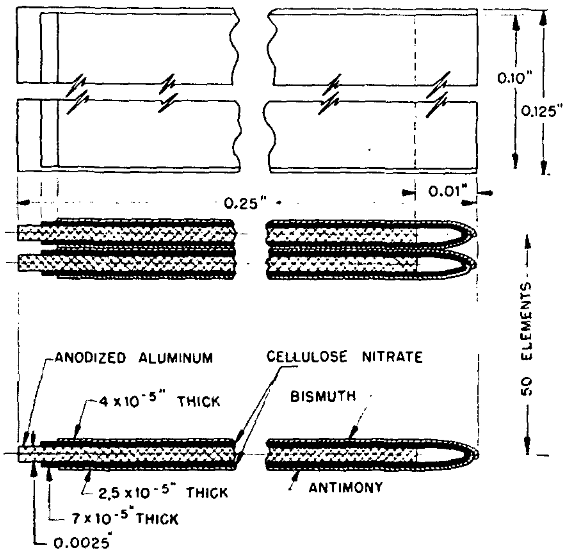


FIGURE 13. Folded thermocouple stack (not drawn to scale).

The following method of depositing bismuth and antimony upon cellulose nitrate by evaporation was adopted. A weighed quantity of the pure metal, previously cast in vacuum, was evaporated from electrically heated boats. A tantalum boat was used for bismuth and a molybdenum boat for antimony. The heater current was increased gradually during the process so that at the end the boat from which antimony had been deposited had reached a red heat and the other a yellow heat. The evaporation was carried on stepwise, first a layer of antimony and then a layer of bismuth, 25 minutes being required for a complete evaporation process, which took place under a vacuum of 10^{-4} mm Hg.

The progress of the evaporation was followed with an "evaporation meter" situated in the vacuum chamber directly above the boat from which metal was being evaporated. This so-called evaporation meter is made from a glass strip with silver-chromium terminals at the ends. Leads are brought out of the bell jar from the terminals and connected to a "volt-ohmist." As metal becomes deposited on the glass strip during the evaporation process the resistance decreases. The change in resistance may be calibrated to serve as a rough measure of the amount of metal deposited and of its resistivity at the end of the evaporation process. Such meters may be used again and again by simply removing the metal after evaporation by solution with concentrated hydrochloric acid.

Measurements of the Electrical Properties of Evaporated Bismuth and Antimony. Early experiments showed that the amount of metal deposited and its resistivity varied with the evaporation technique as well as with the material upon which the metal was deposited. The results given below are for the metals deposited upon thin films of cellulose nitrate. A strip of the cellulose nitrate used had been weighed previously so that the resistivity of the metals could be calculated. The results shown in Table 1 were obtained using the technique described above.

The bismuth deposits had a dull light-gray appearance; the antimony deposits were a brilliant steel gray and showed a crystalline pattern to the unaided eye.

Alloys of bismuth containing about 5 per cent of either cadmium or aluminum have a lower massive metal electric resistivity than pure bismuth. Although the thermal emf (versus copper) of either of these alloys is smaller, i.e., less negative than for pure bismuth, it might still be more profitable to use these alloys instead of pure bismuth for the negative half of the thermoelements. Only preliminary experiments were made in the evaporation of

TABLE 1

Metal	Thicknesses (microns)	Resistivity (ohm-cm) Average	Resistivity (ohm-cm) Limits	Thermal emf vs. copper (μvolts/degrees C) Average	Thermal emf vs. copper (μvolts/degrees C) Limits
Bismuth	0.73–1.58	168×10^{-6}	$131\text{-}212 \times 10^{-6}$	—57.5	—55.1 to —59.0
	1.64–2.14	159×10^{-6}		—56.1	
	2.05–3.15	130×10^{-6}		—56.0	
Antimony	0.48–1.66	95×10^{-6}	$60\text{–}119 \times 10^{-6}$	35.5	33.1 to 38.6

alloys before it was discovered how to obtain thin deposits of bismuth as well as of antimony with the comparatively low resistivities given in Table 1. Accordingly, the study of evaporation of the alloys was not pursued further.

The Backing Support for the Metals. The supporting material upon which the metal is deposited by evaporation should have the following properties.

1. It must be an insulator.
2. The product of heat capacity, density, and thickness (thermal mass) should be smaller than that of the metals, if possible.
3. It should be stiff at the thickness used.
4. It must be capable of being bent sharply through 180 degrees without cracking.
5. It must withstand the temperature and thermal shock of evaporation.
6. It must have a low vapor pressure.

Early investigations indicated that a rather extensive study would be required to find the ideal material. Although cellulose nitrate is not the ideal material, it satisfies most of the requirements and was used until a more suitable material could be found. Cellulose nitrate films as thin as 1.75×10^{-4} centimeter lend themselves easily to the various operations encountered here.

The cellulose nitrate films were formed by the "knife method," wherein the film solution was poured on a glass plate and spread accurately to the proper thickness with a spreader bar or "knife." The films were then cut to 9x1.2 cm on the glass plate and floated off on water, ready to be mounted.

Mounting or Folding the Cellulose Nitrate. In order to obtain a uniform fold of the cellulose nitrate film it was necessary to fold it over a "bar" which was removed after the fold had set. Various plastic materials were tried, which could be removed with solvents to which the cellulose nitrate is inert. However, better results were obtained using a nylon thread held taut by a spring, the thread being withdrawn mechanically after the fold had set.

All subsequent operations were facilitated by mounting the lower ends of the cellulose nitrate folds on aluminum strips 9 inches long, 0.25 inch wide, and 0.0025 inch thick (see Figure 13). The aluminum strips were cut, straightened, anodized and then mounted in a holder which kept them taut. The distance (0.010 inch) from the top edge of the anodized strip to the fold of the cellulose nitrate film was controlled by the spacing of the (0.003-inch diameter) nylon thread. The adhesion of the cellulose nitrate to the anodized strip was effected by painting glyptal solution, three-fourths of the width, along the length and on both sides of the strip. If the painting is continued over the full width, breaks often occur at the film-aluminum edge.

The holder (Figure 14), with the anodized strip and the nylon thread, was submerged in a vessel filled with water to the surface of which the cellulose nitrate film is transferred. The film was oriented so that its long axis coincided with that of the strip. The water was then drained from the vessel so that as the water surface receded the film followed and was left in the folded position adhering to the anodized strip. After the films on the strips had dried, the nylon thread was withdrawn and the

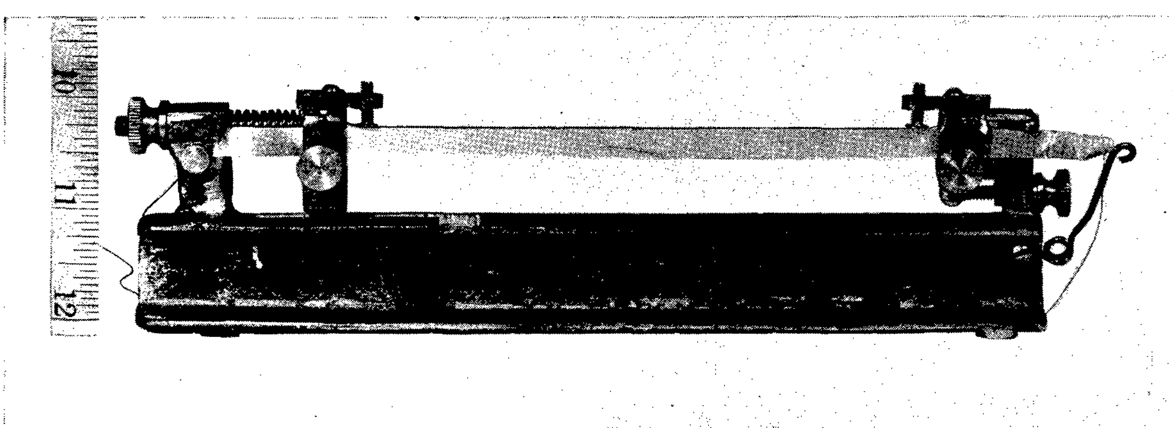


FIGURE 14. Holder with anodized strip.

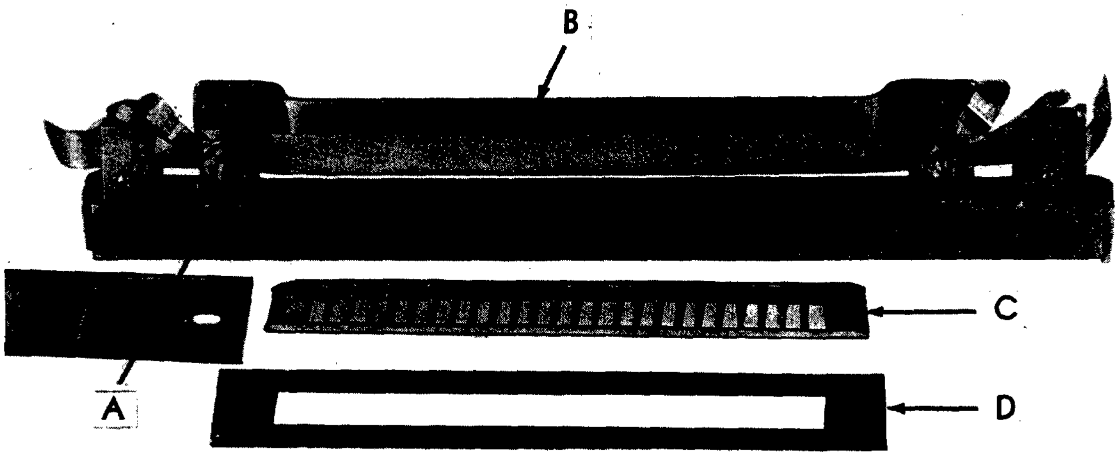


FIGURE 15. Evaporation frame for evaporated thermopile.

strip with the attached film was ready to be transferred to the evaporation frame.

Frames for Holding Strips during Evaporation. The evaporation frames limit the deposition of each metal to one side of the folded cellulose nitrate strip and to an overlap of about 0.15 millimeter at the fold. Each frame consists of four main parts, illustrated in Figures 15 and 16. (A) holds the strip taut yet extendible (by means of a spring); (B) serves as a supporting back for the strip; (C) is a gold mask 0.0015 inch thick which helps to hold that part of the film which extends beyond the edge of the anodized strip down against the supporting back (B), and which also confines the metal deposits to bands 2.5 millimeters wide with a bare space 0.7 millimeter wide between the bands; (D) holds the gold mask in place.

After one metal has been deposited, the frames are removed from the bell jar, parts B, C, and D are transferred to the opposite side of part A, and the second metal is evaporated. Evaporation is accomplished on four strips simultaneously. From each strip 22 thermal elements 0.125 inch wide can be cut.

Stacking and Mounting of Thermopiles. The folded strips were then cut along the bare spaces into individual thermoelements, using an instrument similar to a paper cutter. The resistance of each

FIGURE 16. Evaporation frame for evaporated thermopile, assembled.

element was measured with a special testing clamp the jaws of which grip the element 0.3 millimeter back from the fold. Those elements having resistances greater than 1.75 ohms were discarded.

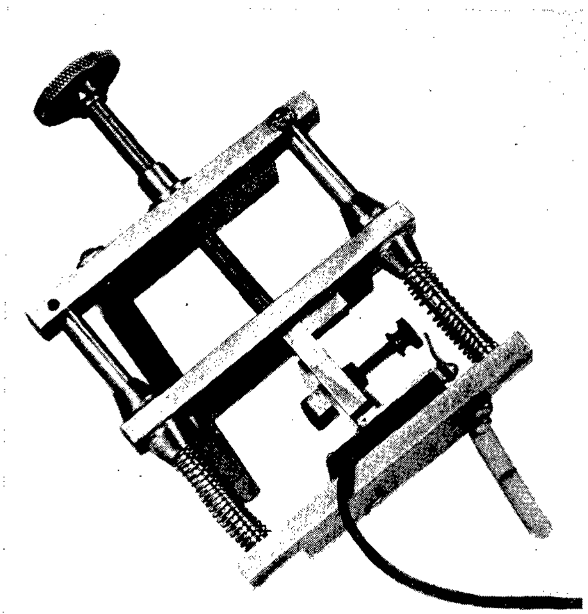


FIGURE 17. Device for stacking Harris thermoelements.

The elements were then stacked in groups of 50 in the "stacker" shown in Figure 17. Top and bottom electrodes are silver strips 0.1x0.25x0.005 inch. The bottom silver electrode was put into the stacker first, then the elements were put into place individually, the edges of the folds coming up against a glass plate. As the stacking was continued it was often necessary to improve the alignment of some of the elements. After 50 elements had been stacked, and the top silver electrode inserted, the middle plate of the stacker was slid down and pressure applied through a screw until a minimum resistance, usually about 60 ohms, was obtained. The outer side and the back of the pile were painted with cellulose nitrate, thus cementing the elements into the finished pile. Figure 13 illustrates one of the elements and also shows how the elements are arranged in a completed thermopile.

The cemented piles were then put into a "skeleton" of the final housing and coated with gold "black."

The skeleton was inserted into the outer casing of the housing and the piles were ready for use. Figure 18 shows four stacks of piles in a skeleton designed for the Bureau of Ships; Figure 19 shows the skeleton in its case.

PHYSICAL CHARACTERISTICS OF HARRIS THERMOPILES

Table 2 lists the physical data obtained on four Harris thermopiles designated A, B, C, and D. The two designated A and B were adjacent to each other in one housing and constituted the pair tested under Contract OEMsr–1168, while C and D were adjacent to each other in another housing.

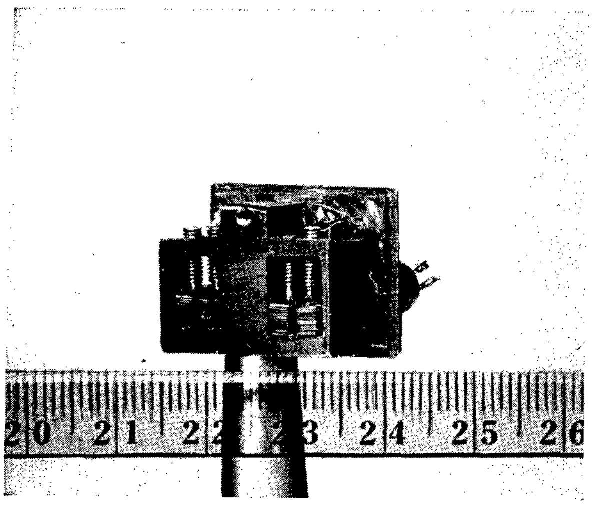


FIGURE 18. Four stacks of piles in skeleton.

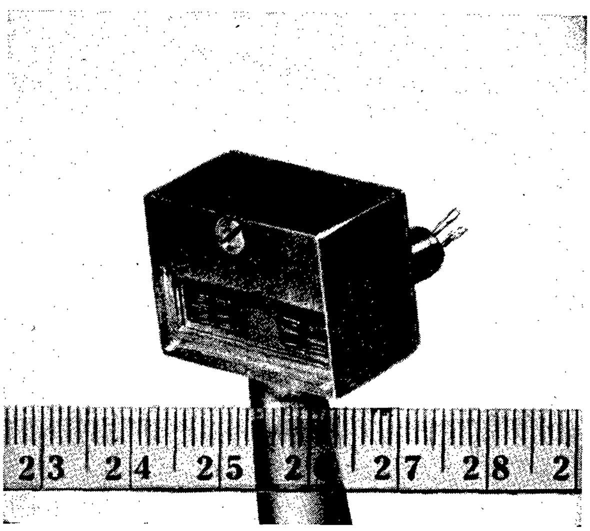


FIGURE 19. Skeleton in thermopile case.

TABLE 2. Physical dimensions and properties of Harris thermopiles.*

	A	B	C	D
Length from "hot" to "cold" junction	0.25 mm	0.30 mm	0.35 mm	0.15 mm
Width of each element	2.5 mm	2.5 mm	2.5 mm	2.5 mm
Thickness, antimony	0.6×10^{-4} cm	0.6×10^{-4} cm	0.6×10^{-4} cm	0.6×10^{-4} cm
Thickness, bismuth	1.07×10^{-4} cm	1.07×10^{-4} cm	1.07×10^{-4} cm	1.07×10^{-4} cm
Thickness, cellulose nitrate	1.7×10^{-4} cm	1.7×10^{-4} cm	3.2×10^{-4} cm	3.2×10^{-4} cm
Number of junctions in pile	50	50	50	25
Active receiving area of pile	0.11 sq cm	0.11 sq cm	0.09 sq cm	0.05 sq cm
Thermopile resistance	63 ohms	84.5 ohms	56 ohms	32.5 ohms

* All the receivers were covered with gold "black." Thermal emf (measured) Bi-Sb = 92 volts per degree C.

PERFORMANCE CHARACTERISTICS OF THE HARRIS THERMOPILE

Static Characteristics. As discussed under "Static Method," Section 8.3.8, the d-c responsivity of thermopiles A and B was measured under Contract OEMsr–1168. The d-c responsivity for these thermopiles was also found by those working under Contract OEMsr–1147 and included in the contractor's progress report,[3] along with the responsivity of two other thermopiles designated C and D. These values have been grouped in Table 3.

TABLE 3. D-C Responsivities of Harris thermopiles.

	A	B	C	D	Series A+B	Series C+D	Parallel A+B
OEMsr–1147							
Volts/watt	0.40	0.467	0.52	0.15	0.431	0.386	0.202
Area (cm²)	0.11	0.11	0.09	0.05	0.22	0.14	0.22
OEMsr–1168							
Volts/watt	0.345	0.375					

It may be seen that although the responsivities of A and B determined under OEMsr–1168 are somewhat lower than those determined under OEMsr–1147, they are in substantial agreement. The responsivities of A, B, and C are very nearly identical, while the responsivity of D is much lower. In Table 2, it may be observed that D has only half as many junctions as A, B, or C. The heat loss for D is greater than for A, B, or C because of the shorter distance between the hot and cold junctions. The responsivities obtained with the piles in series (Table 3, columns 5 and 6) serve as a check on the measurements and prove that the voltage generated is roughly proportional to the number of junctions. The ENI, defined under 8.3.3, was determined for thermopiles A and B by Contract OEMsr–1168 at the two frequencies 14.6 cycles and 27.6 cycles, using an amplifier sharply tuned to the two frequencies. The ENI values found are listed below in Table 4.

TABLE 4. ENI values for the Harris thermopiles determined with 5 μ to 14 μ radiation.

Thermopile	ENI(14.6 c) (μw)	ENI(27.6 c) (μw)	MENI(14.6 c) (μw)
A	0.2	0.2	0.009
B	0.25	0.25	0.01

As was suggested in Section 8.3.3, when the gain and frequency pass band of the amplifier and the resistance of the thermopile are known, the output voltage to be expected from the thermal-agitation noise may be computed. At frequencies of 14.6 cycles and 27.6 cycles, the observed noise was 27 db and 20 db, respectively, above the computed value. Moreover, the noise observed with the thermopile in the circuit was essentially no different from the noise observed with the thermopile shorted out. This would seem to indicate that most of the observed noise originates within the amplifier. If it were possible to eliminate the amplifier noise so that the only noise present were that of the thermopile, the noise level might be expected to be reduced by the corresponding factors. The ENI under these conditions, i.e., the MENI, would be as listed in Table 4, column 4.

The frequency-response curves of thermopiles A and B, as determined by the method outlined under "Frequency Response," Section 8.3.7, is shown in Figure 20. No time constant can be ascribed to the frequency response of these thermopiles as the curves are not of the proper shape. The measurements on A and B reported by Contract OEMsr–

1147 and shown in Figure 21 are in good agreement with those shown in Figure 20. Although thermopile C has substantially the same d-c responsivity as A and B, its response to interrupted radiation, as shown in Figure 21, is much less than that for A and B. This is because its cellulose nitrate backing is much heavier. Because of its greater heat-loss rate, D should be faster than C. That this is true is made evident from Figure 21 by the flatter response curve for this thermopile.

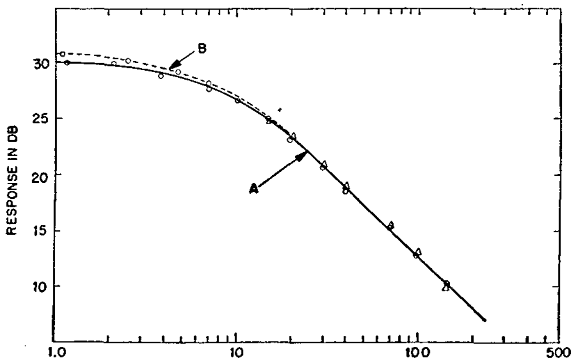


FIGURE 20. Frequency-response curve for Harris thermopile.

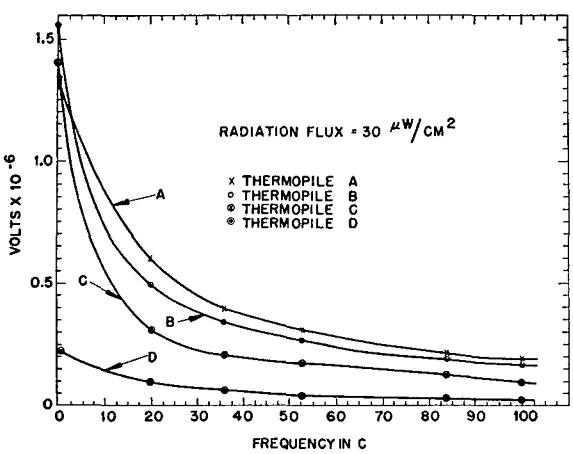


FIGURE 21. Response of thermopiles to interrupted radiation.

Measurements on the blackness of the receiving elements, made as described in Section 8.4 under "Frequency Response" and shown in Figure 22, reveal that the Harris thermopiles are uniformly black throughout the spectral range from 1 μ to 14 μ.

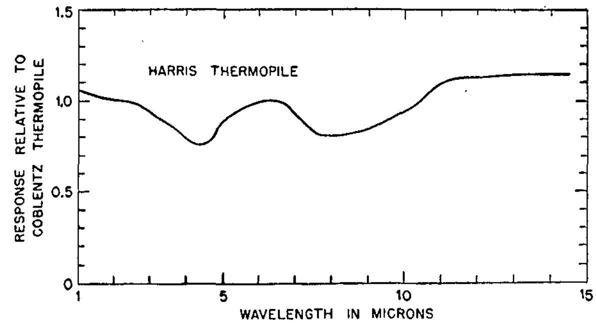


FIGURE 22. Spectral response curve for Harris thermopile.

8.6 THERMOPILES NOT DEVELOPED IN SECTION 16.4

8.6.1 The Weyrich Vacuum Thermocouple

The Weyrich thermocouple was not submitted to those working under Contract OEMsr-1168 by NDRC or by any other agency interested in infrared detectors. This thermocouple has, however, been used extensively over a long period of years by infrared spectroscopists and is, therefore, important as a detector. The device is a thermopile with two junctions which may be used as the receiving elements for infrared radiation. Each of these junctions has a receiving area of 0.02 square centimeter coated with zinc black. The thermoelectric materials are two antimony-bismuth alloys.

Two leads for each junction emerge through vacuum seals, so that the junctions may be joined externally in series aiding or in series opposing or in parallel. The resistance of each junction was found to be about 10 ohms.

To determine the d-c responsivity, the thermocouple was connected to a Leeds and Northrup high-sensitivity galvanometer and illuminated by radiation of known flux density. The thermal emf produced caused a galvanometer deflection which was compared with that from 1 μv introduced into the circuit. From the area of the element (0.02 square centimeter), the responsivity in volts per watt was evaluated, and found to be 0.29 volt per watt.

The frequency-response curve given in Figure 23 was obtained by means of a General Motors amplifier. A ballistic galvanometer method yielded a time constant, assuming one to exist, of 68 milliseconds.

When the thermocouple was evacuated, the responsivity increased by a factor of about 15, and the time constant, measured by the ballistic galvanometer method, increased by the same factor, that is, to about 1,000 milliseconds.

An investigation of the blackness of this thermocouple at various wavelengths of radiation revealed that the thermocouple is as uniformly black throughout the spectrum from 1 μ to 13 μ as the Coblentz thermopile with which it was compared.

8.6.2 The Eppley Thermocouple

An Eppley thermocouple of the type employed in the Farrand device developed for experimental use by the Bureau of Ordnance, Navy Department, was furnished, through BuOrd, to Contract OEMsr–1168 for testing.

In a general way, this thermocouple is similar to the Weyrich type described, although it is probably somewhat more ruggedly constructed and presumably unevacuated. The element consists of two thermal junctions joined in series opposing, each junction being fitted with a blackened receiver, of area 0.01 square centimeter. The resistance was found to be about 5.8 ohms. The responsivity was determined in the same manner as for the Weyrich thermocouple, and was found to be 0.375 volt per watt.

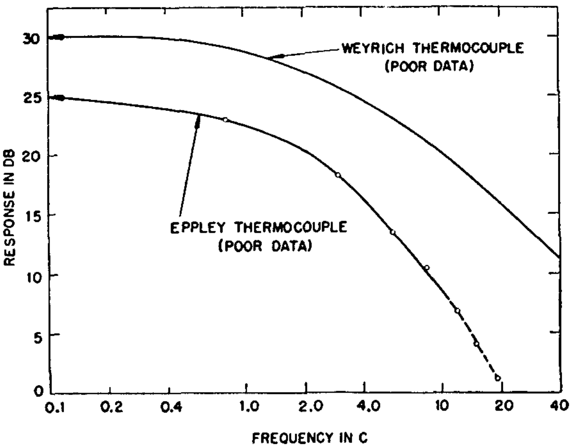


FIGURE 23. Frequency-response curves for Weyrich and Eppley thermocouples.

The frequency response of the Eppley thermocouple was investigated by the use of the General Motors amplifier and is shown in Figure 23. Several sets of measurements indicated that the frequency response was characterized by a time constant of 90 milliseconds. Spectral response curves revealed that this thermocouple is as uniformly black throughout the spectrum from 1 μ to 13 μ as the Coblentz thermopile used as a standard.

8.6.3 The Schwarz Thermopile

The design of the Schwarz thermopile, constructed by Adam Hilger, Ltd., London, England, and furnished for testing by Section 16.4 of NDRC, is substantially different from that of other thermocouples or thermopiles examined. As indicated in Figure 24,

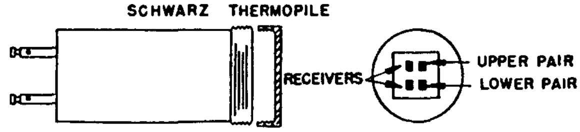


FIGURE 24. Diagram of Schwarz thermopile.

the elements are mounted in a cylindrical case 2.5 centimeters in diameter and 5.0 centimeters long. The thermopile is also shown schematically in Figure 25. Rods of two different metals, sharpened at

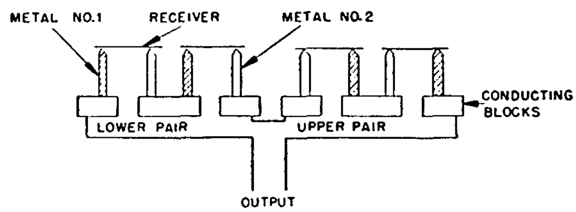


FIGURE 25. Schematic diagram of Schwarz thermopile.

the top end, are mounted in blocks. A thermocouple is made by welding a blackened receiver to the sharpened ends of these rods. The receiver has the dimensions 1x2 millimeters, that is, an area of 0.04 square centimeter when used in pairs. A thermopile is then formed, as indicated in the diagram, of several such couples joined in series. The electrical connections are made through two binding posts fastened to the back end of the case containing the thermoelements. These thermopiles were mounted in the case behind a window made of fluorite and were operated in air at atmospheric pressure. The Schwarz thermopiles are quite delicate and must not be submitted to great mechanical shock.

The resistance of the thermal junctions varies substantially from element to element, since the re-

sistance in any case depends essentially upon the manner in which the receiver is welded to the pointed rods. The resistances of the three Schwarz thermocouples tested under Contract OEMsr-1168 (Nos. B4772/9, 11, and 12) were found to be 23.5 ohms, 51.0 ohms, and 20.7 ohms respectively, while the resistances quoted by Hilger are 20 ohms, 35 ohms, and 20 ohms.

The d-c responsivity of the Schwarz thermopile was obtained exactly as in the preceding cases. The values are summarized in Table 5.

TABLE 5. Responsivities in volts per watt.

	Upper pair	Lower pair	Hilger values
No. B4772/9	0.72	0.75	0.9
No. B4772/11	0.85	1.00	1.2
No. B4772/12	0.65	0.73	0.85

The frequency response for the thermopile was investigated, and a curve showing the observed response, converted into decibels, plotted against the logarithm of the frequency in cycles is shown in Figure 26 for the upper pair of unit No. 11. The zero-frequency response in decibels was also measured and is shown by the arrow in Figure 26. The

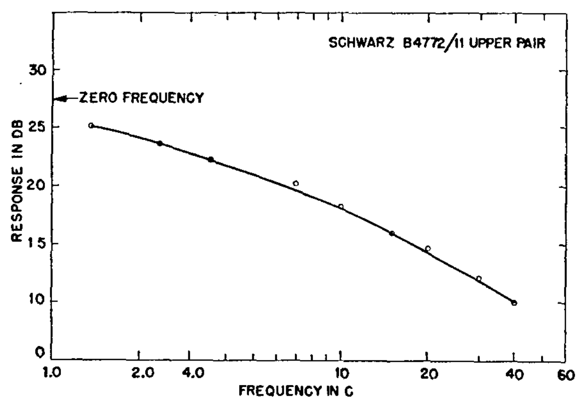


FIGURE 26. Frequency-response curve for Schwarz thermopile.

curve shown is quite typical for all of the Schwarz thermopiles and it shows that the frequency response is not such that a time constant can be ascribed to it.

The ENI was determined at the two frequencies, 14.6 cycles and 27.6 cycles, using a tuned amplifier and a square-wave heat input. The first two columns of Table 6 give the ENI values for all the pairs of the three thermopiles. These ENI values are for Nernst glower radiation, which is principally 2 μ. Radiation of this wavelength was used because the fluorite window of the thermopile is opaque beyond 10 μ. The last column of Table 6 gives the MENI, which is the optimum value for the ENI.

A relative spectral response curve for thermopile No. 12 with the ratio of the Schwarz response to the Coblentz response adjusted to unity at 2.0 μ is shown in Figure 27. It is readily seen that the rela-

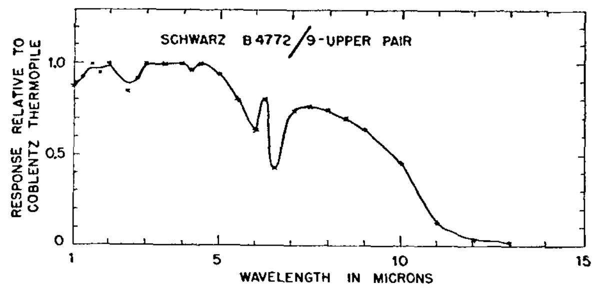


FIGURE 27. Spectral response curve for Schwarz thermopile.

tive response falls off materially beyond 6 μ and becomes quite small at longer wavelengths. This decrease from 6 μ on can be ascribed to the fluorite window used with the thermopile. From 1.0 μ to 5.0 μ the relative response is very nearly unity.

TABLE 6. ENI observed in the 2-μ spectral region.

		ENI (μw) 14.6 cycles	ENI (μw) 27.6 cycles	MENI (μw) 14.6 cycles
No. B4772/9	Upper	0.035	0.05	0.004
	Lower	0.04	0.05	0.005
No. B4772/11	Upper	0.075	0.09	0.009
	Lower	0.075	0.08	0.009
No. B4772/12	Upper	0.05	0.037	0.006
	Lower	0.06	0.05	0.008

8.7 BOLOMETERS

8.7.1 Metal Strip Bolometers

A metal strip bolometer is a device which, by means of a large temperature coefficient of resistance, is capable of detecting very small amounts of radiant energy. It is a low-resistance element and is made of very thin material, usually by an evaporation process. As developed under Contract OEMsr-60 [11] with Harvard University, a metal strip (Strong)

bolometer consists of one or more strips mounted within a metal case behind a window capable of transmitting infrared radiation. The bolometers usually operate in hydrogen at reduced pressures.

When used to detect heat radiation, two bolometers are generally connected in series to the primary of a transformer, the secondary of which is capable of matching the impedance of the first tube of the amplifier (Figure 28). The center tap of the

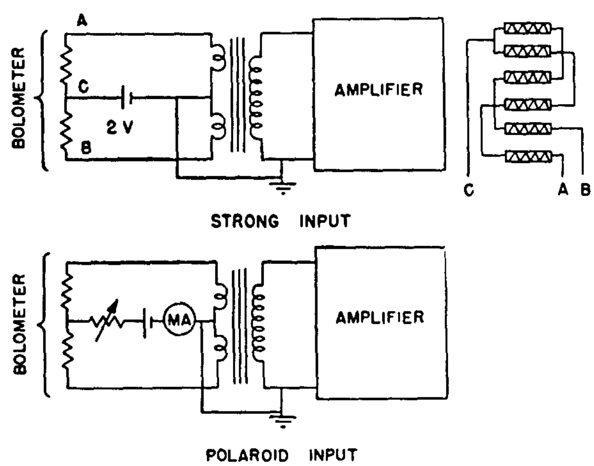


FIGURE 28. Input circuit for Strong and Polaroid bolometers.

transformer primary is connected through a battery to the junction of the two strips to furnish the appropriate voltage across the bolometer. When interrupted radiation falls on one of the bolometers, an alternating emf is generated and impressed on the grid of the first tube by means of the transformer.

Production of Bolometer Strips

Nickel strips have been used effectively for bolometers. The method of preparing them (Contract OEMsr-60) involves a composite coat: silver, aluminum, and nickel are deposited, successively, by the evaporation process, on the clean freshly broken edge of a glass plate. Later, the composite layer is separated from the glass, and the other metals are dissolved from the nickel. Strips formed on such edges are characterized by sharp unbroken borders.

The various steps in making a nickel bolometer strip are outlined in the paragraphs which follow.

The more or less straight edge of a broken glass plate, of 0.5 to 1 millimeter thickness, is coated with a thin transparent film of silver to provide a base layer which later can be stripped off the glass.

Next, a deposit of aluminum, of 0.5 to 1 μ thickness, is formed over the silver. The purpose of this aluminum deposit is to afford a means by which the nickel can be freed of silver, and also to give the strip strength during the operation of separating it from the glass by peeling.

Finally, an evaporated coat of nickel, of about 0.25 μ thickness, is deposited over the aluminum layer.

The composite three-film coat is peeled off the glass edge with tweezers. The operation is facilitated by applying a drop of water which contains a wetting agent. The composite strip is then dipped in a beaker containing caustic solution. The aluminum interfilm dissolves in this solution and carries the silver away at the same time. The remaining nickel strip is rinsed several times with water until all the caustic is removed. The nickel strip is finally removed from the rinse water on a strip of paraffin paper 0.5 inch wide, on which it is allowed to dry.

Bolometer Construction

A bolometer is made by attaching one or more nickel strips to appropriate terminals by means of soft solder, as follows: The terminals are first separately tinned with a small soldering copper, then they are wetted with soldering flux by means of a fine ink pen; the strip is laid across the terminals and adjusted in place—the flux acts as a lubricant and facilitates the adjustment of the strip; finally, each terminal is slowly heated with the small soldering copper until the flux dries and the end of the strip becomes "wetted" with the solder on the terminal.

Mounted strips are coated with aluminum black by letting evaporated aluminum black (aluminum evaporated from a tungsten coil under a hydrogen pressure of 3 millimeters of mercury) settle onto them.

Windows. Rolled sheets of AgCl, of $\frac{1}{64}$-inch thickness, have been adopted as window material for bolometers. They are attached with Sealstix cement or glyptal lacquer and are protected from solarization by means of a coat of gilsonite (after Pfund) which is dissolved in benzene and applied to the window with a fine brush. A thin uniform coat of gilsonite, which does not attenuate the visual transmission of the AgCl by more than 50 per cent, effectively prevents its decomposition by the action of light.

It is necessary to avoid a direct contact between AgCl sheets and brass, since on contact a reaction between these materials sets in which results in the complete disintegration of the AgCl. To avoid this reaction, the window frame of a brass bolometer can be formed from a layer of fine silver, which may be either soldered in place or deposited by electroplating. AgCl is stable in contact with fine silver.

Bolometers made from 0.25-μ nickel strips and intended for operation at about 40 cycles are evacuated and then filled with hydrogen at a pressure of about 1 millimeter of mercury. At this pressure the conductive cooling by this gas is still high, while the convective cooling is attenuated some 760 times from its value for atmospheric pressure. Since variations of convective cooling, at atmospheric pressure, give rise to strong spurious microphonic signals, whereas the conductive cooling at low pressures does not, this choice of pressure is advantageous. The use of a separate charcoal chamber provides a means for absorbing other gases which are absorbed more strongly than hydrogen by the charcoal. This separate chamber can be made of brass or glass, and attached to the bolometer, remotely, by means of ⅛-inch outside diameter copper tubing. During evacuation of the bolometer, the trap is advantageously baked out at a temperature of about 300 C.

Application of the Nickel Carbonyl Process to Bolometer Construction

The manufacture of metal or nonmetal bolometers in quantity presents problems because of their delicacy. When this was realized, a method of construction was devised and tested which promises to avoid some of these problems. By this method the bolometer strips (of any material not attacked by CO) are formed on a nickel base which is later removed by reaction with CO to form $Ni(CO)_4$. The list of metal strip materials to which the method may be applied excludes nickel (and, to a certain extent, iron) but gold or rhodium are suitable. Nonmetal strips or other thin films, for example, thin quartz films, have been made by this process.

The metal and nonmetal bolometer strips which have been made by this process under Contract OEMsr-60 include gold, nickel oxide, Ag_2S, and quartz. They have not been made at ordinary pressure but rather at 200 atmospheres pressure of pure CO at 200 C. The process was carried out in heavy-walled glass containers. The thin unsupported quartz films were made by first evaporating quartz on a heated nickel backing to obtain the quartz film in an annealed condition.

The advantage of this carbonyl method of making strips and films lies in the fact that the composite starting strips are sturdy during all the operations of construction; and further, the nickel backing is finally removed without even subjecting the bolometer material to the forces of surface tension or to the tearing action of bubbles formed, as when a surrounding metal is removed by solution in acid or alkali reagent.

Both $Ni(CO)_4$ and CO are very poisonous and suitable precautions must be taken to prevent breathing these gases.

Tests of the Strong Bolometer

The one metal-strip bolometer unit constructed and furnished for testing by Harvard University under Contract OEMsr-60, consisted of six blacked nickel strips connected as shown in Figure 28. Each strip is about 1.2x4.8 millimeters and thus about 0.057 square centimeter in area. Because of the resistance of the transformer, wires, and current-measuring equipment, the working voltage across three strips of the bolometer was about 1 volt. The strips were mounted and encased as previously described.

Static Characteristics of the Strong Bolometer. By a voltmeter-ammeter method, the resistance of the bolometer strip was measured while its temperature was varied, the temperature being determined with a calibrated thermocouple. From the slope of a graph of R_b versus T, the temperature coefficient of resistance α was found to be 0.0045 per degree centigrade.

The variation of the bolometer resistance as a function of the d-c power input was measured by means of a Wheatstone bridge powered by a storage battery with a variable resistance in series. The power to the bolometer strip was varied by changing the current supplied to the bridge. As the current in the bolometer was also measured, the power expended in the strip could be computed for each resistance measurement. Figure 12 shows the graphs of R_b versus P and R_b versus I_b. The quantity dR_b/dP for any operating current was obtained from the R_b versus P curve of Figure 12. In the tests reported here the bolometer current was 0.24 am-

pere, and dR_b/dP for this current was about 6.6 ohms per watt.

As not all of the heat power which fell on the bolometer was effective in causing resistance change and because radiation of different wavelengths was not necessarily equally effective, it was not sufficient to measure only dR_b/dP. The resistance change per watt of heat power dR_b/dH or the absorptivity a_λ had also to be determined. By direct measurement (see Section 8.3.8) dR_b/dH for 2 μ radiation was found to be 2.54 ohms per watt, and a_λ for 2 μ radiation had the value 0.38.

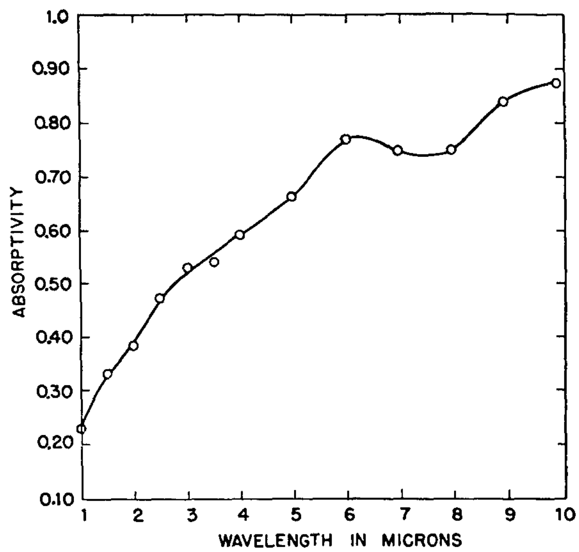


FIGURE 29. Absorptivity curve for Strong bolometer.

The spectral response of the bolometer from 1 μ to 10 μ, measured with a Hilger rock salt prism spectrometer, was compared with the response of the Coblentz thermopile over the same spectral range. The ratio of the bolometer response to Coblentz response, arbitrarily fixed at the absorptivity value 0.38 at 2 μ, was plotted versus wavelength and is shown in Figure 29. The absorptivity increased by about a factor of 2 in going from 2 μ to 6 μ. This may be explained on the assumption that the transmission of the silver chloride window was appreciably better at 6 μ than at 2 μ, as the silver chloride had been exposed to light for some time.

It is not known whether this measured increase in absorptivity can be considered reliable, because it was also found that the voltage output per watt of heat input in the 7-μ to 14-μ wavelength range was not so much greater than the same relation in the 2-μ region as the absorptivity curve would suggest. The receiver was quite uniformly black throughout the region investigated. During the course of the experiments, the original silver chloride window was replaced with one of polished rock salt. An increase of voltage output by a factor of 2.5 was noted in the 2-μ region. Rock salt has, in general, a more uniform and higher transmission than silver chloride throughout the infrared range.

Dynamic Characteristics of the Strong Bolometer. The frequency response of the Strong bolometer was observed from 1 cycle to 250 cycles by a method similar to the one described under "Frequency Response," Section 8.3.7, and under Section 8.4. A curve was made for each one of the elements and, as they proved to be nearly identical, an average response curve was drawn and is shown in Figure 30. The response for 1 cycle to 40 cycles was measured separately from the 10-cycle to 250-cycle range, the latter being the more reliable. The two curves do not have quite the same slope in the range where they overlap, but the indicated 3-db drop from zero-frequency to 10 cycles is not an unreasonable one. As the asymptote approached by the curve at high frequencies was somewhat steeper than that to be expected if the bolometer had a time constant, none has been computed. The behavior may be read directly from the curve.

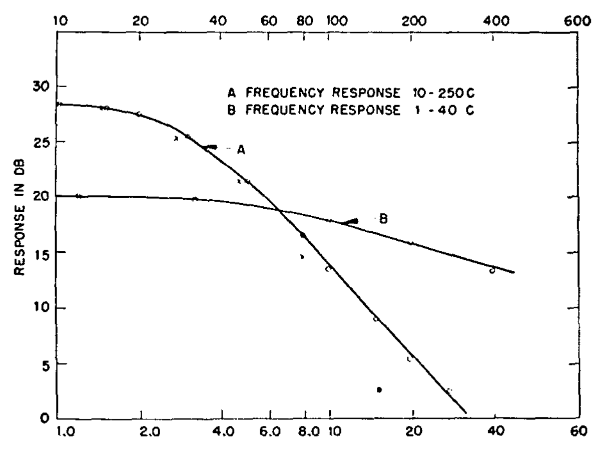


FIGURE 30. Frequency-response curves for Strong bolometer.

The ENI was measured for a variety of frequencies by a method described in "Heat Sources," Section 8.4. An amplifier which could be made to tune sharply at frequencies 14.6, 27.6, 47.0 and 80

cycles was used for these measurements. The values obtained are given in Table 7. In column 4 may be seen the effect of the replacement of the silver chloride window with rock salt. In addition to the ENI, values of the minimum detectable signal were obtained as outlined under "Minimum Detectable Signal," Section 8.4. A record of signal and noise on the same chart taken at 27.6 cycles is shown in Figure 6, indicating a signal just above the noise.

TABLE 7. The ENI values for the Strong bolometer.

Frequency (cycles)	ENI (μw) electric black body (AgCl window)	ENI (μw) NBS standard lamp AgCl window	NaCl window	MENI (μw) AgCl window
14.6	0.03	0.04	0.02	0.005
27.6	0.06	0.08		0.009
47.0		0.10	0.03	
80.0	0.14	0.13	0.04	0.035

Calculations of the thermal agitation noise inherent in this bolometer were made as outlined in Section 8.3.2 and were found to be 12 to 18 db less than the observed noise output, depending upon the frequency. The output noise was 0.3 to 0.35 volt for all frequencies used with the tuned amplifier. If the noises arising in the amplification system could be reduced so that the thermal agitation noise of the bolometer was the only important contribution to the total noise output, then there would be a corresponding improvement in the ENI. This MENI, computed from the experimental ENI values obtained for 5-μ to 14-μ radiation, is given in Table 7.

From the static characteristics and frequency response of the bolometer and the gain of the amplifier, the output voltages at the frequencies of 14.6, 27.6, 47.0, and 80 cycles have been predicted and are found in column 6 of Table 8. In column 7 are shown the values of the output actually measured. The ratios of the predicted output to the measured output for any given frequency are found in column 8. It may be seen that in the case of poorest agreement the ratio is 1.7 and for the best the ratio is 1.13. This is considered to be good agreement.

Later gain measurements indicate that the tabulated values are high and that better agreement between the expected and measured output would probably have been obtained with the later amplifier gain measurements if the bolometer measurements had been repeated.

8.7.2 Thermistor or High-Impedance Bolometers

Thermistor material is a semiconducting substance which has a large negative temperature coefficient. A thermistor is, therefore, a resistor, the resistance of which changes rapidly with temperature. A bolometer constructed of this material is a device which may be used to detect or measure small quantities of radiant heat energy which cause a temperature rise in the material. As finally developed under Contract OEMsr–636 with BTL, a typical thermistor bolometer consists of one or more flakes of thermistor material cemented on a backing which in turn is in good thermal contact with a metal case having a window which permits infrared radiation to pass through it. The sensitive flakes are from one to several millimeters long, a few tenths of a millimeter wide, and about 10 μ thick.

When used as a bolometer, one or more of these flakes are connected electrically in one or more arms of a single Wheatstone bridge circuit. Electrical current is passed through the flakes and two contacts of the bridge are connected to the input of a high-gain amplifier. This multiplies the electrical voltage developed in the bridge and delivers it to various forms of indicating devices, such as meters, recorders, cathode-ray tubes, or headphone.

TABLE 8. Expected outputs and measured outputs for Strong bolometer.

Frequency (cycles)	G_r	dR_b/dH (ohms/watt)	I_b (amp)	ϕ	Expected dE_{out}/dH (volts/μw)	Measured dE_{out}/dH (volts/μw)	Ratio
14.6	1.55×10^8	2.54	0.24	0.684	29.2	17.2	1.7
27.6	0.80×10^8	2.54	0.24	0.537	11.8	8.2	1.44
47.0	0.80×10^8	2.54	0.24	0.335	7.35	6.5	1.13
80.0	1.40×10^8	2.54	0.24	0.182	6.91	4.3	1.61

When no radiant energy falls on the bolometer, the bridge is usually balanced and the indicating device is quiet. However, when radiant energy falls on one of the bolometer flakes, an increase in temperature is produced and the bolometer resistance is reduced. The bridge is thereby unbalanced and delivers a small voltage to the amplifier which in turn operates the indicating mechanism.

Such a bolometer and amplifier combination is capable of detecting about 0.1 μw in several milliseconds. The temperature of the flake is increased by about a 10^{-6} C, and the amplifier receives about 1 μv. The resistance of a flake is about a megohm and about 100 volts are required to operate it. Since these values depend on the area of the bolometer and on its operating conditions, they are meant to convey orders of magnitude only.

How Thermistor Bolometers Are Made

It is desirable in practice to form the thermistor element first and then attach it to the backing proper for the particular application for which it is to be used. The following discussion of the formation and assembly of the bolometer has been condensed from the report [12] on this subject issued under Contract OEMsr–636.

In order to make the resistance of the bolometer element conform to a desired value for any particular size and shape, a proper choice of material is necessary. For example, one or more of the oxides of manganese, nickel, cobalt, or copper may be used. The majority of units requested to date have called for a resistance in megohms, lengths from 1 to 6 millimeters, and a thickness of about 10 μ. A combination of the oxides of manganese, nickel, and cobalt has been found suitable for meeting these requirements. In a few cases the oxides of manganese and nickel have been used.

In order to provide a thin and sufficiently homogeneous film of resistance material, attention must be paid to the particle size of the material used. It has been found necessary to employ a powder having a maximum particle size of about 0.01 the desired thickness of the completed flake. Mixed oxides of this particular size, a temporary binder, and a volatile solvent were used. The temporary binder most commonly used was polyvinyl butyral, the solvent a mixture of ethyl alcohol and amyl acetate. These materials were placed in a ball mill and ground to a homogeneous liquid mix. A few drops of this material were then placed on a flat glass surface and spread to a uniform thickness by a properly spaced straightedge. The solvent was then allowed to evaporate in a dust-free atmosphere. The dried film was removed from the plate by dampening with water and stripping from the surface of the glass. After being cut to the desired size, each flake was placed on a thin plate of platinum which had been coated with a thin layer of aluminum oxide, the purpose of which was to prevent the flakes from sticking to the plate during the subsequent firing operation.

The temperature of the furnace was gradually raised from room temperature through 400 C and finally to some point between 1100 and 1400 C to complete the sintering, depending on the material from which the flakes were made. When cool the flakes were removed by a suction device and stored in a suitable container. At this point they were ready for attachment of terminals and subsequent mounting. Up to this point in the process, practically all the operations were done in multiple; thereafter the operations were performed individually with some emphasis given to manipulative dexterity.

To each end of the flake an electrode was then attached. This was done by applying a paint (platinum black No. 505 made by Hanovia Chemical and Manufacturing Company) to the contact area, drying out the oil of rosemary solvent, and firing to some temperature between 800 and 860 C. The painting operation was done under a microscope with a small stylus.

Care was taken in the painting operation to wet the desired area thoroughly and so produce a well-defined line between the contact and the active area of the flake. After being fired, the contact area had a continuous metallic coating which was in very intimate contact with the thermistor substrate. This was essential to insure contact with a definite active area over the range of current and temperature for which the flake was to be used; otherwise, various types of electric noise render the flake useless.

Following the application of the contact, one end of a 0.001-inch diameter platinum wire lead was fastened to it by means of a platinum-silver alloy paste. A suitable material for this purpose is a platinum alloy paste, No. 18, also made by Hanovia. This material has a somewhat higher flux content than the No. 505 and is also less rich in platinum.

The paste securing the lead was fired as given above for the contact.

When the terminals were attached to the flake, the active area and resistance were completely fixed. If the flakes were to be used in bolometer units requiring that the active areas and/or resistance of two or more flakes be matched, the desired resistance and dimensions were determined and filed with each individual flake so that desired matching could be done. Up to the present time, all requirements of width of active area had been met without selection. The length requirements are met by a very large percentage of flakes as now produced. In cases where the resistances of two (and in one application four) of the flakes used to form a bolometer unit were to be closely matched so they could be incorporated in bridge circuits, a selection was made from a comparatively large stock.

After such matching as was required by the design of a particular bolometer in which the flakes were to be used, they were cemented to a backing structure. The cement most frequently used for this operation was bakelite resin BR–0014. This is a thermosetting cement whose principal ingredient is the uncured resin. Since its thermal conductivity was more than tenfold lower than that of the thermistor flake material or of most backing materials of practical interest, the thickness of this cement layer was of considerable importance. It was generally desirable to have it as thin as practicable.[c] If the layer was too thin, however, poor mechanical contact between the flake and the backing resulted. The flake was applied to the backing as follows.

A camel's hair pencil brush was used to apply a properly thinned coat of resin to the backing material. The back of the flake was then wetted with a drop of similar material and, while the backing was still wet, the flake was applied to it and manipulated back and forth to give closer contact. The alcohol solvent was then dried out of the cement by baking the assembly at 80 C for 16 hours. During this period partial curing of the bakelite resin also took place. The complete curing was effected by a two-hour baking at 125 C.

In most applications the backing consisted of a block of solid material of which the mass was large compared with that of the flake. The backing material was selected on the basis of the time constant desired for a particular application. Where low time constants are desired the backing must have high thermal diffusivity. Backing materials used in various units to date are quartz, glass, anodized aluminum, silver with a thin electrically insulating layer of mica interposed between the flake and the metal block, etc. Unbacked units have also been made in which the cooling agent has been air or helium, occasionally at less than atmospheric pressure. In unbacked units a supporting structure has been used in lieu of the backing. One such structure has been a set of 0.020-inch diameter wires sealed into a glass bead to serve as "posts" to which the terminal wires of the flake can be attached. Another has been made by undercutting one of the above backing structures just beneath the active area of the flake. The backed flake assembly was then fastened into the base of a housing or capsule. This was done by fastening the backing surface and housing together with cement (No. 624N, B. B. Chemical Company). The principal adhesive component is synthetic rubber.

This base was in each case designed to fit the equipment into which it was to be subsequently mounted. All housing bases, however, consisted essentially of a metal shell into which the necessary number of lead wires were hermetically sealed to accommodate the flake assembly. A cap covered over the base to form the complete capsule. This cap consisted of a silver element into which a silver chloride window was welded after treatment with gilsonite or silver sulfide to make it opaque to visible and ultraviolet light.

The above description is generally applicable to bolometer units. One unit, the Penrod type, has been chosen to illustrate a particular assembly. Figure 31 shows the component parts (roughly 1½ times actual size) and indicates the steps in its assembly. The large black strip to the left is the thermistor sheet before firing; the two adjacent pieces have been cut from it; the next two strips have been fired. The next two strips have platinum contacts and leads; the strips are next shown on the backing block prior to insertion into the mount.

This mount is shown in four stages of assembly on the upper layout. The three pins to the left are glass-covered cunife wires which are inserted and cemented into the three holes visible at the end of

[c] In one application of importance, a layer of paper 0.0004 inch thick was first attached to the quartz backing with the BR–0014 cement. The purpose of the paper was to serve as a spacer to make the effective cement layer thicker.

the first view, as shown in the second view. The third view of the mount shows the thermistor flakes with their backing block in place. The platinum leads are soldered to the cunife wire ends. Below the third view, starting at the bottom of the window sections, is the silver chloride disk, the silver window frame, then the two welded together. The window area is shown coated with gilsonite. The final assembly at top right is a completed unit with silver window frame soldered to the main body.

thermistor flakes were mounted parallel with each other and close together on the same backing. Table 9 lists the information furnished by BTL on the bolometers sent for testing. The necessity of completely terminating Contract OEMsr–1168 by October 31, 1945, made it impossible to test all of the BTL bolometers completely. The information obtained on bolometers, for which measurements were completed, is contained in Table 14. The interpretation of the sensitivity symbols will be considered later under "Sensitivity." In Table 9 the bolometers are listed according to material, backing, and number of elements.

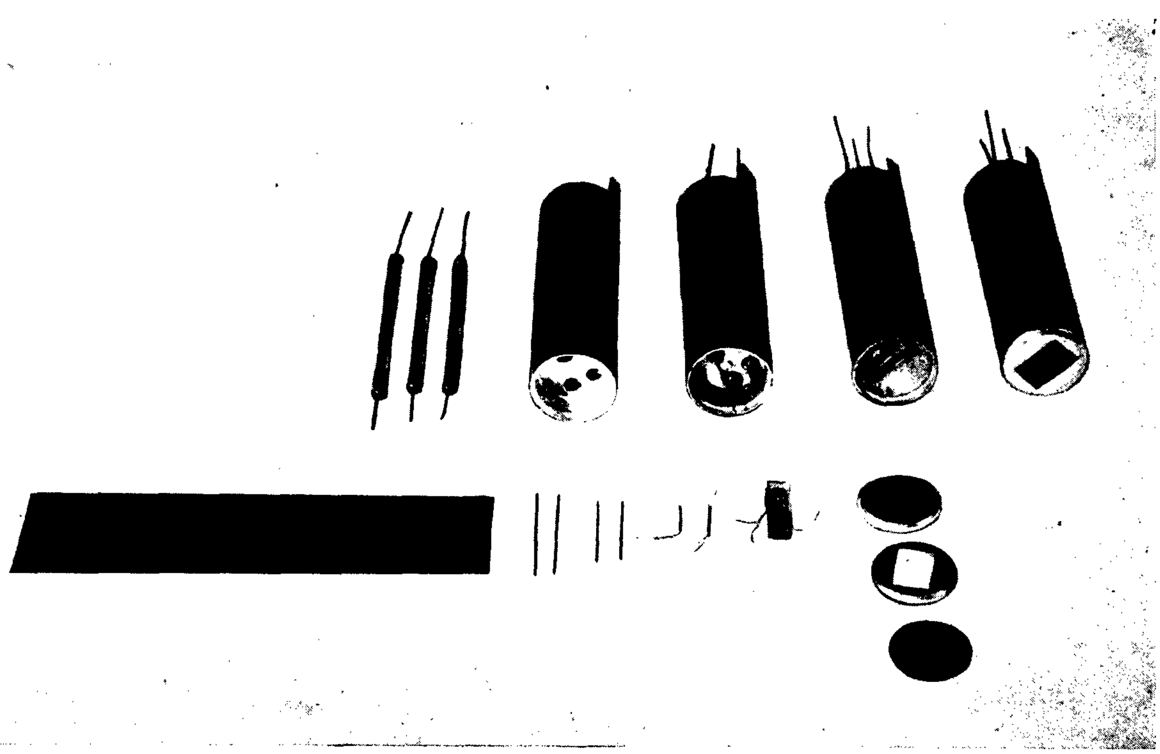


FIGURE 31. Component parts of Penrod type bolometer.

TESTS ON BTL THERMISTOR BOLOMETERS UNDER CONTRACT OEMSR–1168 [2a]

Through Section 16.4 of NDRC a number of BTL thermistor bolometers were sent to Ohio State University for testing. Two kinds of thermistor material were used. The bolometers made from one kind had resistance from 20 to 30 megohms at room temperature; from the other, 3 and 4 megohms. They were single and double-element types intended for push-pull or balanced operation. Within each class were unbacked designs and others backed by glass or quartz. In the double element design the

An amplifier used in these tests was built by the Western Electric Company, BTL Contract OEMsr–1098,[17] especially for use with thermistor bolometers. It was a high-gain design using twin-T feedback networks to obtain a very sharp pass band (noise pass-band width of 2 cycles) centered at 15 cycles. The amplifier output was available both as a 15-cycle voltage and as a rectified current sufficient to operate a 5-milliampere Esterline-Angus recording meter. Though the gain of the amplifier

TABLE 9. Description of BTL bolometers.

Bolometer	Width (mm)	Length (mm)	Separation (mm)	Area (sq cm)	τ (msec)	$S_b']^{15c}_{100v}$ (v/w/sq cm)	$S_b]^{15c}_{100v}$ (v/v)
	No. 1 Material, air-backed, one-element type with NaCl window						
XB-241	0.207	3.10	....	0.00642	...	1.55	242.0
XB-242	0.206	2.98	....	0.00614	...	1.29	210.0
	No. 2 Material, air-backed, one-element type with NaCl window						
XB-108	0.199	2.91	....	0.00579	...	1.36	234.0
XB-239	0.195	3.00	....	0.00585	...	1.32	226.0
XB-240	0.203	3.00	....	0.00609	...	1.32	216.0
	No. 2 Material, glass-backed, one-element type with NaCl window						
S-19	0.202	2.981	....	0.00602	5.9	0.938	156.0
XB-237	0.202	3.00	....	0.00606	7.6	0.675	111.0
XB-238	0.194	3.03	....	0.00588	7.6	0.738	126.0
	No. 2 Material, quartz-backed, one-element type with NaCl window						
S-20	0.207	3.017	....	0.00625	3.1	0.415	66.5
XB-235	0.200	2.95	....	0.00590	3.0	0.329	66.0
XB-236	0.201	2.96	....	0.00595	3.0	0.366	61.5
No. 2 Material, glass-backed, two-element type with AgCl window (the AgCl has sulfide on the top side)							
PND-108 left	0.202	2.951	0.401	0.00596	10.1	0.637	107.0
PND-108 right	0.203	2.964		0.00602	8.6	0.622	103.0
PND-118 left	0.195	3.045	0.403	0.00594	8.6	0.646	109.0
PND-118 right	0.197	3.020		0.00595	8.6	0.676	113.0
No. 2 Material, quartz-backed, two-element type with AgCl window (the AgCl has sulfide on the top side)							
PND-104 left	0.195	2.963	0.400	0.00578	5.2	0.558	96.6
PND-104 right	0.194	3.021		0.00586	5.2	0.551	94.1
PND-125 left	0.193	3.085	0.401	0.00597	3.7	0.382	64.1
PND-125 right	0.195	3.060		0.00597	5.7	0.687	115.0

was adjustable in 2-db steps, a gain of 118 db from the grid of the first tube to the output measuring instruments was usually employed.

The bolometer and leads to the amplifier were mounted in a 0.25-inch diameter copper tube filled with paraffin with the head protruding for irradiation. This arrangement served not only to shield the input circuit but also to prevent microphonic pickup.

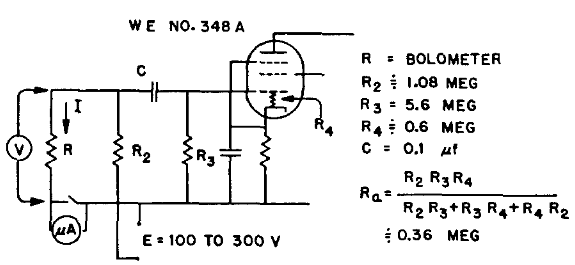


FIGURE 32. Input circuit for BTL bolometer.

The input circuit is shown in Figure 32. The heat power to be detected was chopped at 15 cycles by a sector wheel and allowed to fall on the bolometer R. The 15-cycle changes in the bolometer resistance produced corresponding voltage changes which were amplified by the tuned amplifier.

Static Characteristics of Thermistor Bolometers. The resistances of the various elements were measured with a Wheatstone bridge as the temperature was varied over the range 0 to 60 C. It was found that the resistance could be quite accurately represented by an equation of the type[13] $R = A \exp (\beta/T)$ where β is a constant (Figure 33). This is typical of semiconductors. The resistance of the bolometer elements was also measured as the applied voltages and current were varied. From these measurements the curves shown in Figure 34 for XB-108, S-19, and S-20 were drawn. These curves, which are substantially identical with those furnished by BTL under Contract OEMsr-636, are representative,

hence curves for the others are not shown. The curves indicate the interdependence of voltage, current, resistance, and power when the bolometer in its housing is at room temperature. From the data

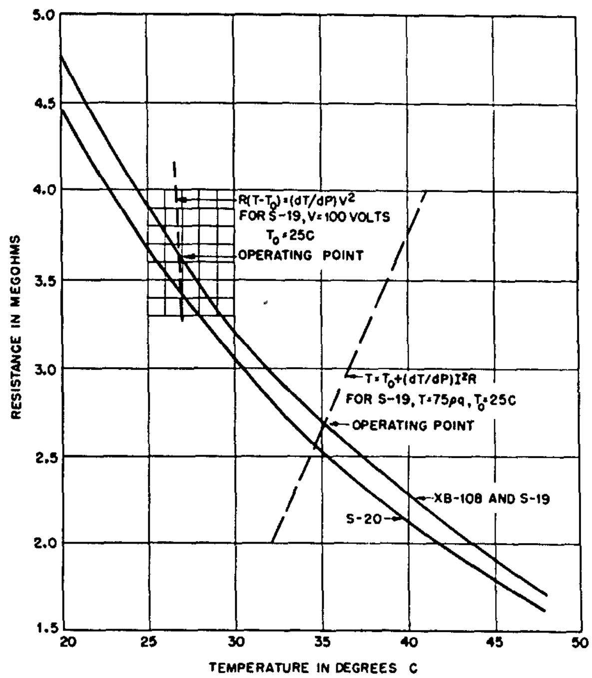


Figure 33. Curves showing static characteristics of BTL bolometers.

furnished by such curves as are shown in Figures 33 and 34, it was observed that dT/dP was a constant for each bolometer. The values of β and dT/dP for the bolometers are found in Table 10.

In Figure 35 is shown the exponential heating and cooling curve for an unbacked bolometer with sensitivity plotted as ordinate and time plotted in seconds as abscissa.

The PND bolometers consist of two bolometer flakes mounted on the same piece of backing material. The temperature of each one of the flakes will tend to increase with an increase in the temperature of the other. It is easily seen that for identical (or similar) flakes $dT_1/dP_2 = dT_2/dP_1$, where the subscripts distinguish the two flakes, regardless of the flake material and size and regardless of the nature of the backing material. This equality was experimentally verified.

By changing the amount of electrical power input to one flake while measuring the resistance of the other flake it was possible to measure dR_1/dP_2. The known $R - T$ relation for the flakes then permitted a determination of dT_1/dP_2. The statically determined values of dT_1/dP_2 were: for PND-108, 184 C per watt; for PND-118, 167 C per watt; and for PND-125, 83 C per watt.

It is to be expected that the ability of one flake to affect the other would depend upon the frequency at which the flakes are heated. The frequency responses show that this coupling between the flakes is negligible at the operating frequency of 15 cycles. The coupling is important, however, in establishing the d-c operating temperatures.

Table 10. Values of β and (dT/dP) for BTL bolometers.

Bolometer	β (°K)	dT/dP (°C/watt)
XB-108	3430	5,270
XB-235	....*	198
XB-236	....*	187
XB-237	....*	501
XB-238	....*	535
XB-239	....*	4,050
XB-240	....*	4,000
XB-241	3800	3,950
XB-242	3810	6,170
S-19	3390	678
S-20	3369	275
PND-108L†	3310	400
PND-108R†	3310	400
PND-118L	3310	430
PND-118R	3310	430
PND-104L	3310	260
PND-104R	3310	260
PND-125L	3310	193
PND-125R	3310	255

* $\beta = 3400$ is the value quoted by BTL for No. 2 material.
† L and R refer to the left and right flake of a pair.

Dynamic Characteristics of Thermistor Bolometers. The frequency response of the bolometers was measured beginning with a frequency of 1 cycle in a manner similar to that described in Section 8.3.6 and under "Amplifiers," Section 8.4. By means of a d-c amplifier, the d-c response was correlated with the response at some frequency greater than 1 cycle. The frequency-response curves of the various BTL bolometers tested are shown in Figures 36 to 39, inclusive. The height of the zero-frequency response is indicated by an arrow at the left edge. For purposes of comparison, there is shown in Figure 34 the responses to be expected if the time constants (and sensitivities) listed in Table 9 were the sole factors determining the frequency responses of the S-19 and S-20 units. The usefulness of the

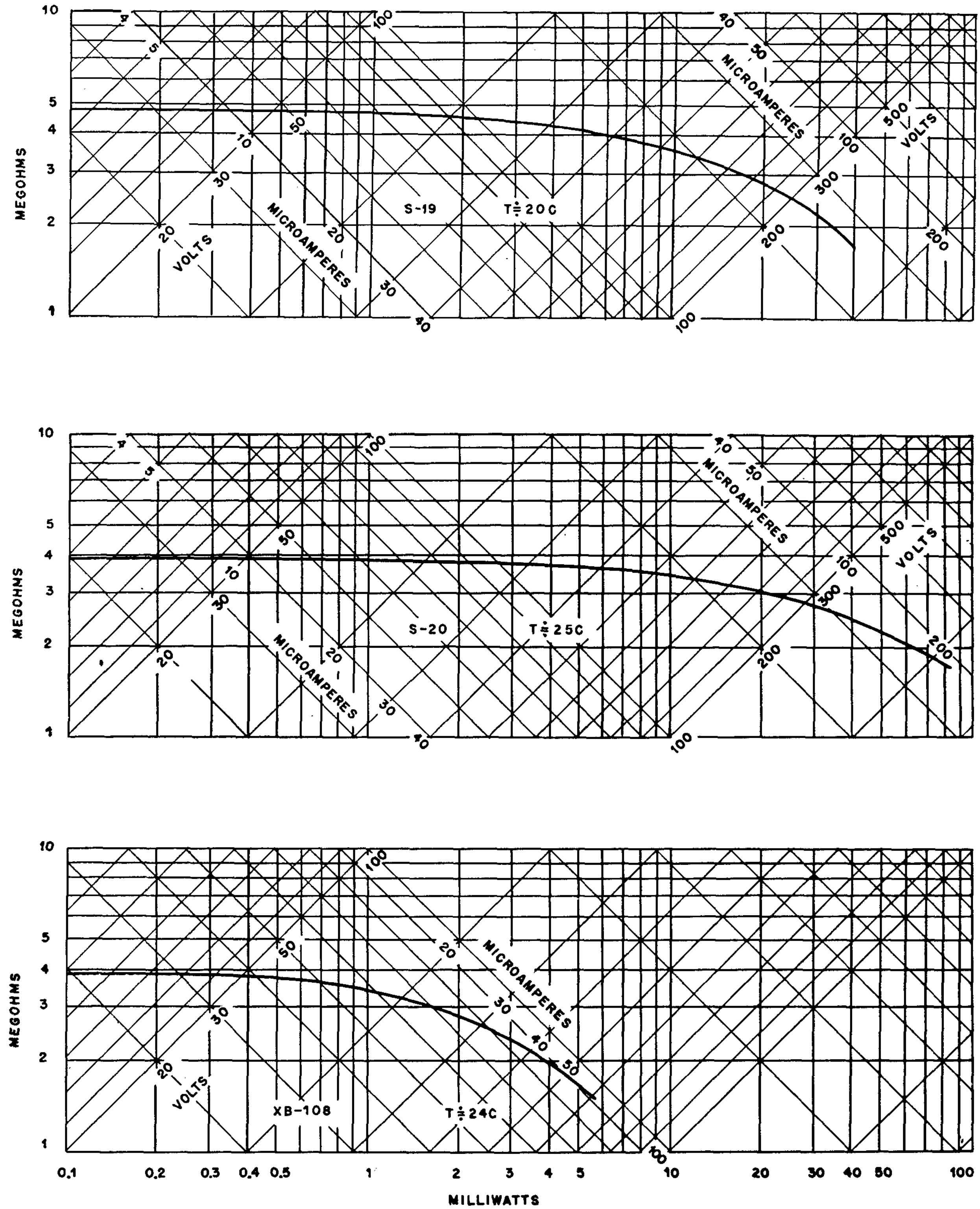


FIGURE 34. Curves showing static characteristics of BTL bolometers.

time constants quoted in Table 9, in predicting the frequency response, can be judged from these curves. The danger of incorrect extrapolation to zero frequency and the danger of using the zero-frequency sensitivity with the time constant to predict the behavior is clear from this figure.

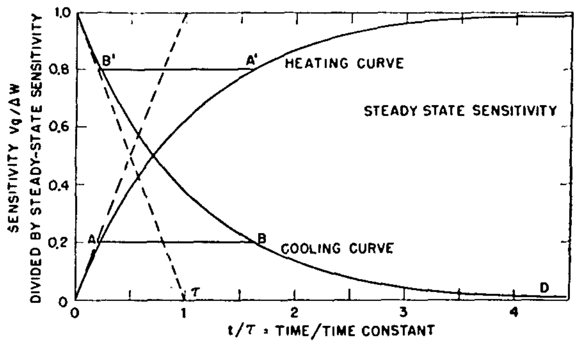


FIGURE 35. Exponential heating and cooling curves for unbacked BTL bolometer.

However, BTL has found it convenient to think of the behavior of the solid-backed bolometers from the point of view that they possess several time constants. Figure 40 shows a curve in which sensitivity is plotted versus time of irradiation. It may

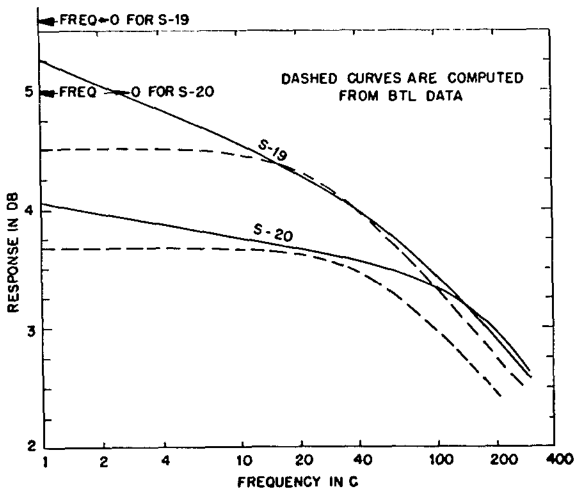


FIGURE 36. Frequency-response curves for BTL bolometers.

be seen that up to 10 milliseconds the data fit an exponential curve which has a definite steady-state sensitivity and a time constant. The experimental curve, however, keeps on rising as if it were tending to approach a second steady-state sensitivity at $t = 1$ second, then rises again, approaching a final steady-state sensitivity at 10^3 seconds. As a rough approximation, it could perhaps be said that the complete curve consists of the sum of a series of exponential curves, each having its appropriate steady-state value and time constant. When a bolometer is used as a heat detector only the high-frequency portion of the frequency-response curve is of interest, as the exposure times rarely exceed two or three times the time constant associated with this portion of the curve. For each of the units S–19 and S–20, the first time constant has the values listed in Table 9.

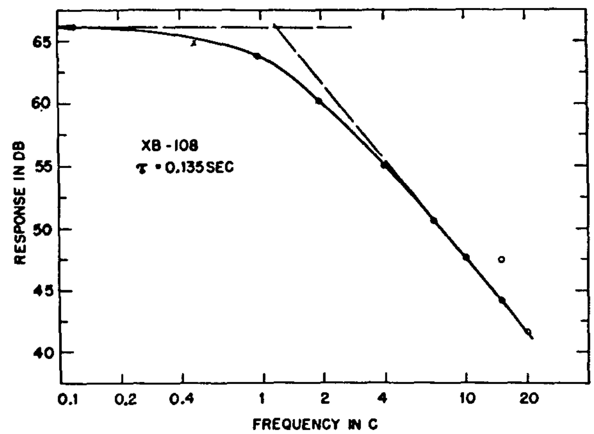


FIGURE 37. Frequency-response curves for unbacked BTL bolometer.

With the air-backed unit XB–108, however, the response shown in Figure 37 indicates that the zero-frequency sensitivity and a single time constant of 135 milliseconds will serve to predict the complete frequency response almost exactly. A curve of sensitivity versus time of irradiation would obey an exponential rise to a steady state, as shown in Figure 35.

The frequency-response curves of the other BTL units were measured and it was found that the pairs indicated by braces in Table 9 had nearly the same values. For this reason only the responses of one of each of the pairs has been included in Figure 38. The typical response characteristics for air-backed, glass-backed, and quartz-backed units are easily distinguished. The time constants of the air-backed units are about as follows: XB–239, 73 milliseconds; XB–240, 76 milliseconds; XB–241, 122 milliseconds; and XB–242, 122 milliseconds.

It was observed that the frequency responses were slightly different when the radiation was sharply

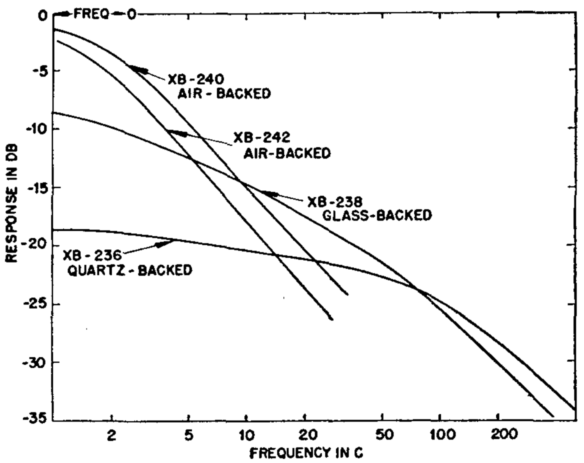


FIGURE 38. Frequency-response curves for BTL bolometers.

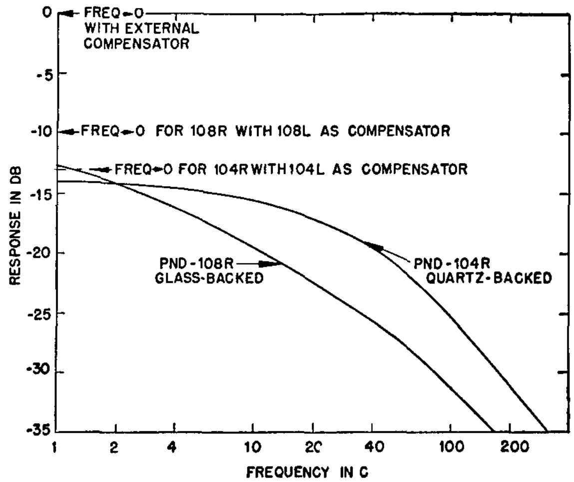


FIGURE 39. Frequency-response curves for BTL bolometers.

focused on the bolometer than when diffusely spread. This might be expected because diffuse radiation would produce a general heating of the housing, backing, connections, etc. This is consistent with the observation that the frequency response was altered only in the 0- to 3-cycle region. Only a few decibels difference in response was noted for the variations in the incident radiation which were measured. The frequency responses shown in the figures were obtained with a sharply focused image of a Nernst glower on the bolometer strip. This should produce a bolometer heating more nearly like the electrical heating produced in the static tests and should give better correlation with these tests.

The frequency-response curves of the two-element PND models are shown in Figure 39. The PND–104 does not appear to have a time constant, but for frequencies greater than 1 cycle the response is roughly approximated by a 5- to 6-millisecond time-constant response. The two flakes in these PND models are mounted in close proximity on the same backing, and, because of this, the operation of one flake is not independent of the other. This can be observed when only one element of a pair is illuminated and the other element is used as a compensating resistor. Under this situation the ratio between the zero-frequency response and the 1-cycle response is much less (about 10 db) than when an element of another bolometer is used as a compensating resistor. This indicates that the compensating flake in the PND is heated by conduction through the backing when the neighboring flake is irradiated. The frequency response for values greater than 1 cycle was not materially affected by using an external compensating resistance in place of the neighboring flake in the PND models.

The ENI values for the bolometers were determined as outlined under Section 8.3.3 and under "Heat Sources," Section 8.4. The noise from the amplifier (118 db gain from the grid of the first

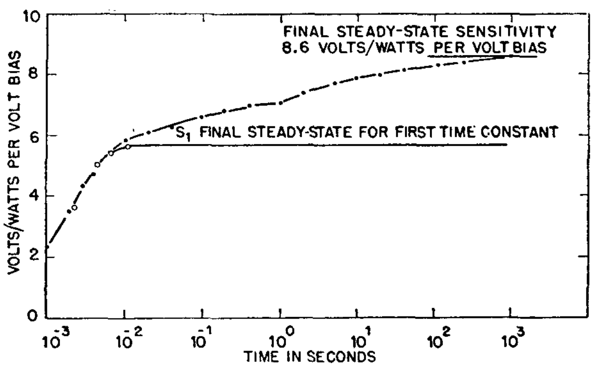


FIGURE 40. Frequency-response curve for BTL bolometer.

tube to the output meter) was about 0.1 volt for all of the bolometers tested. This noise was about 3 db above the expected Johnson noise from the input circuit. The ENI values were, therefore, proportional to the operating sensitivities. The smallest ENI values observed using the low-temperature black body described under "Heat Sources," Section 8.4, are listed in Table 11.

It should be emphasized that the ENI listed in

this table, as well as other ENI values in this chapter, are for the whole assembly of bolometer and amplifier. A change in the pass-band width would, of course, change the ENI.

TABLE 11. ENI values for BTL bolometers.

Bolometer	ENI (μw) observed	Bolometer voltage	Bolometer voltage for max sensitivity
XB–108	0.008	75	86.5
S–19	0.004	202	242.0
S–20	0.009	208	366.0

A practical estimate of the merit of the heat detection system may be formed from the record shown in Figure 9. This record was obtained on an Esterline-Angus recording milliammeter as suggested in Section 8.4. The rectifier in this case, however, was built into the BTL amplifier.

Sensitivity. Bell Telephone Laboratories Contract OEMsr–636 has used the symbol $S_b]^{15\,c}_{100\,v}$ (Table 9) to mean the rms voltage output of the bolometer bridge network per peak-to-peak watt of radiation falling on the bolometer under the conditions that the voltage across the bolometer be 100 volts; that the heat input be interrupted 15 times per second with equal times on and off; that the amplifier pass band be wide enough to preserve the essential waveform of the signal delivered by the bolometer bridge network to the amplifier; and that the bridge factor must be unity.

A different definition of sensitivity which is convenient to use here is denoted by the symbol $s]^f_V$. This is defined as the rms voltage across the bolometer per rms watt of heat radiation falling on it, under the conditions that the heat input be modulated sinusoidally at f cycles, the bridge factor be unity, and the d-c bolometer voltage be V. Since the output of the bolometers to a 15-cycle square-wave heat input is essentially of triangular waveform, the above definition of sensitivity is related to the BTL definition by the equation:

$$(2.22)S_b]^{15\,c}_{100\,v} = s]^{15\,c}_{100\,v}.$$

This equation will serve to correlate the values of Table 9 and the theoretical and experimental values which were obtained under Contract OEMsr–1168. The sensitivity of $s]^f_V$ is nearly proportional to V. Actually, $s]^f_V$ is proportional to V/T^2, but as the temperature of the bolometers with $\beta = 3400$ degrees C rises only from 298 (ambient) to 320.1 K for maximum sensitivity, the sensitivity may be taken to be nearly proportional to the bolometer voltage V. T and V are not both independent variables after the ambient temperature has been fixed. If this proportionality is made use of, an approximate sensitivity for 100 volts can be computed from the experimental value obtained for any other voltage. This relation has been verified experimentally.

In order to compute the performance to be expected from a bolometer, it is necessary to know either its voltage or current. Because the thermistor bolometer is used in a high-impedance bridge circuit, more care and better equipment is required to measure the voltage than the current, so in the present investigation, currents were measured. With this current, the operating bolometer resistance and temperature were obtained from the R-T curves by a graphical construction as shown for unit S–19 in Figure 33. A straight line, determined by the relation $T = T_0 + (dT/dP)I^2R$, where T_0 is the ambient temperature and I is the bolometer current, was drawn. The intersection of this line with the $R - T$ curve is the operating point (R and T) of the bolometer.

If it is desired to obtain the operating point when the bolometer voltage is given, the relation $R(T - T_0) = (dT/dP)V^2$ may be used. The complete hyperbola need not be obtained. Two points on the hyperbola close to the R-T curve, preferably on opposite sides, may be used with a linear interpolation between these points. This method is also illustrated for S–19 in Figure 33.

Because the XB–108 unbacked unit cannot be used with a potential as high as 100 volts (cf. Figure 34), and because the S–19 and S–20 backed units can be used with operating potentials greater than 100 volts, the sensitivity $s]^{15\,c}_{100\,v}$ does not tell the whole story. This sensitivity is not the maximum usable sensitivity, but the latter may easily be predicted by the following relation derived in succeeding paragraphs.

$$\text{Max } s^f = (R_0 dT/dP)^{1/2} a\phi_f (0.105) \text{ volts per watt,}$$

where R_0 is the bolometer resistance at $T_0 = 25$ C, a is the absorptivity factor, ϕ_f is the factor accounting for the smaller sensitivity at f cycles per second than at 0 cycles per second, and (0.105) is a con-

stant depending only upon $\beta = 3400$ C and $T_0 = 25$ C. The values of R, T, I, and V at this operating point are

$$R = R_0\ (0.455)\ \text{ohms}$$
$$T = T_0 + (22.1)\ \text{C},$$
$$I = (R_0 dT/dP)^{-1/2}\ (6.98)\ \text{amperes},$$
$$V = (R_0 dT/dP)^{-1/2}\ (3.17)\ \text{volts},$$

where the bracketed numbers depend only on β and T_0. The maximum sensitivity was determined for the bolometers for the region of 5 μ to 14 μ, the values being listed in Table 12. While the maximum sensitivity may not be used in practice, the useful sensitivity is proportional to it. If the "burn-out" temperature be the same for all bolometers of the same size and material, then whatever fraction of max $s]^f$ is safe for one bolometer should be safe for the others because this fraction is attained with the same temperature rise. The sensitivities of the units tested under OEMsr-1168 are given in Table 12.

TABLE 12. Sensitivity values for BTL bolometers with radiation in 5-μ to 14-μ region.

Unit	$S_b]_{100}^{15}$ OEMsr-636 (v/w)	$2.22\, S_b]_{100}^{15}$ OEMsr-636 (v/w)	$s]_{100}^{15}$ OEMsr-1168 (v/w)	max $s]^{15}$ (v/w)
XB-108	234	520	372	270
S-19	156	346	350	675
S-20	66.5	148	154	450

Spectral Characteristics. The spectral characteristics of the bolometers were obtained by using them as the receiving elements in a Hilger infrared

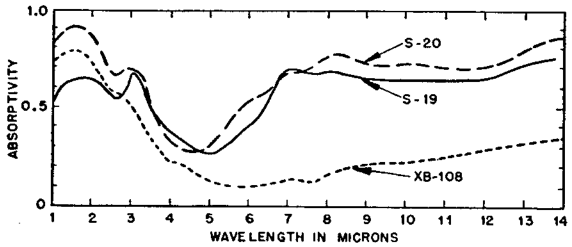


FIGURE 41. Spectral response curve for BTL bolometer.

spectrometer with a Nernst glower source. The linearly amplified outputs of the bolometers were measured as a function of the wavelength of the energy passed by the spectrometer. These outputs were compared with similarly obtained outputs as measured with a Coblentz thermopile. The curves in Figure 41 are the ratios of the bolometer response to the Coblentz thermopile response.

In order to have a more detailed picture of the spectral response, the spectrometer was made automatically recording by coupling the prism drive of the spectrometer to the chart drive of an Esterline-Angus recorder. The records obtained are shown in Figure 42. The four sections of each curve were made by varying the slit widths and amplifier gain so that the recorded region would produce a conveniently measurable response. The records show regions of poor response at 3 μ, 5 μ, 7.5 μ, 9 μ, and 11 μ. The 6.5-μ region is complicated by H_2O absorption, but some of the low responsivity was undoubtedly attributable to the bolometer assembly and some possibly to the window coatings.

It might be supposed from the results shown in Figure 41 that the bolometers transmit an appreciable portion of the 5-μ to 14-μ radiation and that the quartz and glass backings reflect the transmitted portion back into the bolometers. This could explain the better absorptivity of backed than unbacked bolometers in the 5-μ to 14-μ region.

Experiments, reported by Pfund,[14] on the transmission of thermistor material in the infrared show that the transmission increases gradually from zero at about 2.5 μ to about 17 per cent at 6.5 μ. The measurements extend to about 10.25 μ, at which the transmission has decreased to about 13 per cent.

Absorptivity. The output from the bolometer and amplifier for any heat signal can be computed from a knowledge of the static characteristics of the bolometer, the input circuit and amplifier characteristics, and the frequency response of the bolometer unit. In addition, it is necessary to know what fraction of the radiant power incident upon the bolometer is utilized in changing its temperature. This fraction is called the *absorptivity*, and its value has been obtained by taking the ratio of the measured output from a heat signal to the output computed from the measured bolometer characteristics on the assumption that all the radiant heat power incident on the bolometer assembly was absorbed by it. When this factor is included in the calculation of the expected output, the calculated and measured outputs are obviously identical. The only test of the merit of the measurements, then, is the reasonableness of the absorptivity factor.

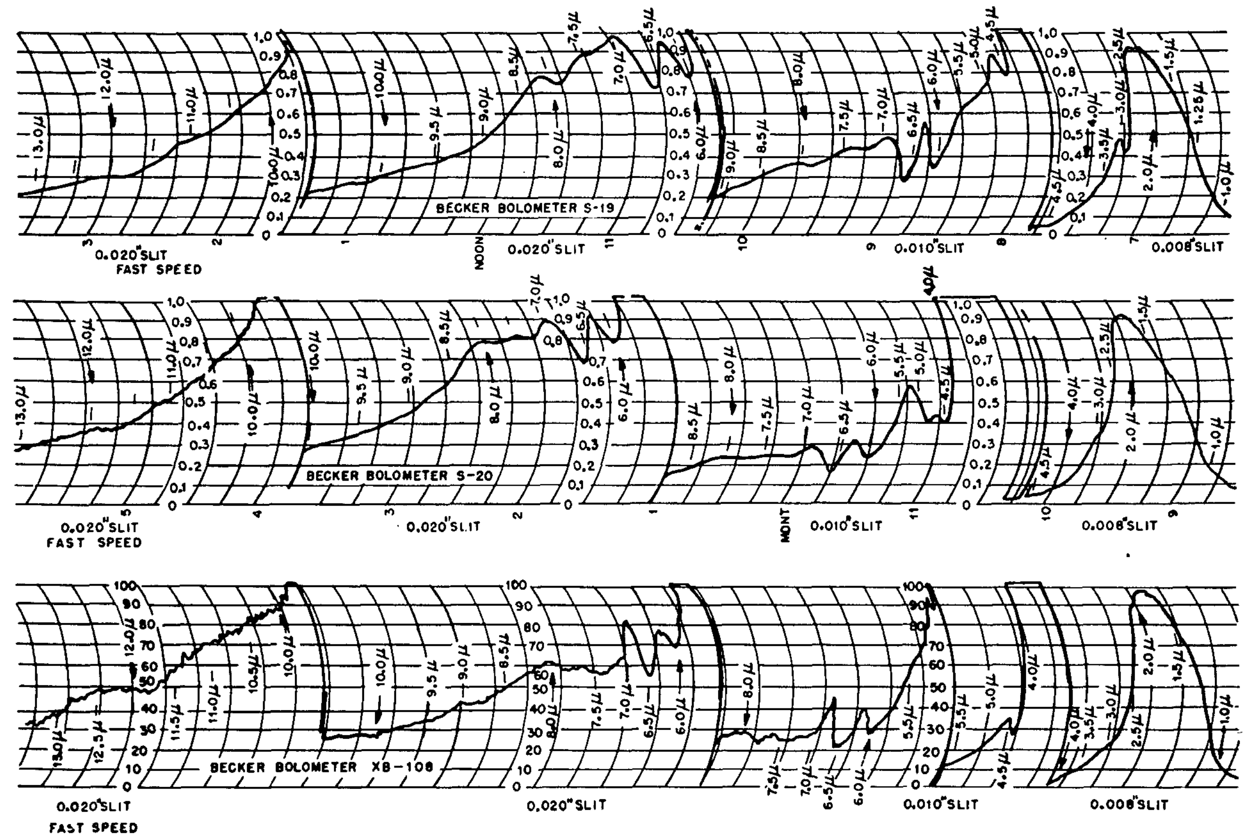


FIGURE 42. Records for determination of spectral-response curves for BTL bolometers.

The absorptivity was evaluated for each bolometer for two kinds of radiation: first, the radiation from a standard lamp source with its peak near 2 μ, and second, the radiation from a black body ranging up to 70 C above ambient temperature. The latter gives a wide band of energy, chiefly in the 5-μ to 14-μ region. The absorptivities of the bolometers are listed in Table 13. These values are consistent with the curves shown in Figure 41 and discussed previously in this section under "Spectral Characteristics." If the absorptivity curve is adjusted to the value computed for radiation from the standard lamp with a peak near 2 μ, the value predicted by the curve for radiation with its maximum in the 5-μ to 14-μ interval agrees with the measured value.

TABLE 13. Absorptivity values for BTL bolometers.

Bolometer	Standard lamp max near 2 μ	Black body max between 5 μ and 14 μ
XB-108	0.72	0.23
S-19	0.64	0.53
S-20	0.87	0.66

8.7.3 Discussion of Equations Pertaining to Thermistor Bolometers

The following paragraphs [15] are devoted to the derivation of relations used in connection with thermistors in this chapter and to showing how the ENI is affected by the bolometer characteristics.

The voltage output per watt of incident radiation at a given frequency was given in equation (11), Section 8.3.6, for bolometers in general. This relation requires some amplification in the case of thermistor bolometers. The voltage into the amplifier per watt of incident radiation is given by

$$s = I \frac{dR}{dT} \frac{dT}{dP} \alpha \varphi F W, \tag{13}$$

where s = volts into amplifier per watt of incident radiation;

I = bolometer current;

R = bolometer resistance;

T = bolometer temperature (degrees K);

P = power (watts) causing the bolometer temperature rise;

a = absorptivity;
F = bridge factor = $R_a/(R + R_a)$ (see Figure 32);
φ = frequency factor = output at operating frequency per output at zero cycles;
W = waveform factor.

Equation (13) may be rewritten with the aid of the thermistor resistance relation (14)

$$R = A \exp\frac{\beta}{T} = R_0 \exp\beta\left(\frac{1}{T} - \frac{1}{T_0}\right) \qquad (14)$$

to read

$$s = IR\frac{\beta}{T^2}\frac{dT}{dP}a\varphi FW = V\frac{\beta}{T^2}\frac{dT}{dP}a\varphi FW, \qquad (15)$$

in which a negative sign has been omitted because the phase relation between output and input is not considered. The temperature rise of the bolometer above ambient temperature T_0 is given by

$$(T - T_0) = \Delta T = \frac{dT}{dP}RI^2 = \frac{(dT/dP)V^2}{R}. \qquad (16)$$

Substituting (14) and (16) in (15) yields

$$s = \left(\frac{R_0 dT}{dP}\right)^{1/2} \left[\left\{\frac{\beta^2\,\Delta T \exp\beta(1/T - 1/T_0)}{T^4}\right\}^{1/2}\right] a\varphi FW. \qquad (17)$$

The bracketed quantity depends only on ΔT, β, and T_0 and can easily be maximized. The bracketed expression will be maximum when

$$3\Delta T^2 + (2T_0 + \beta)\Delta T - T_0^2 = 0. \qquad (18)$$

As the fraction $12T_0^2/(2T_0 + \beta)^2$ is small compared with unity

$$\Delta T = \frac{T_0^2}{\beta + 2T_0} \text{ for maximum } s. \qquad (19)$$

For $T_0 = 25$ C and $\beta = 3400$ (for material No. 2), which is assumed here for all numerical calculations and emphasized by placing the numerical values in brackets,

$$\Delta T = [22.1 \text{ C}].$$

The bracket in equation (17) equals 0.105 for the following values of the terms: $\beta = 3400$ K, $T_0 = 25$C, $\Delta T = 22.1$ C. Hence the maximum value of s is

$$\text{Max } s = \left(\frac{R_0 dT}{dP}\right)^{1/2} [0.105]\, a\varphi FW \qquad (20)$$

and

$$\text{Max } s]^f = [0.105]\left(\frac{R_0 dT}{dP}\right)^{1/2} a\varphi_f. \qquad (21)$$

Max $s]^f$ is computed for $F = 1$ and $W = 1$. Using the value of ΔT for max s, we find that

$$R \text{ (for max } s) = R_0\,[0.455] \text{ ohms,}$$

$$V \text{ (for max } s) = \left(\frac{R_0}{dT/dP}\right)^{1/2} [3.17] \text{ volts,} \qquad (22)$$

$$I \text{ (for max } s) = \left(\frac{R_0 dT}{dP}\right)^{-1/2} [6.98] \text{ amperes.}$$

These relations specify the operating point completely in terms of the bolometer resistance and the effect of the backing on the d-c heat dissipation, dT/dP. The sensitivity also depends upon the backing, because the latter determines the frequency factor φ and may affect the absorptivity a. For a well-blacked bolometer the absorptivity would not be affected by the backing and the merit of the backing could be evaluated by the factor $(dT/dP)^{1/2}\varphi$.

It is also interesting to note that if a group of thermistor bolometers of the same material and same flake size are inserted into the same input circuit, then the bridge factor will be the same for all the bolometers when the supply voltage is adjusted for maximum sensitivity. This condition follows obviously from the fact that the operating resistances will all be the same regardless of the backing.

Figure 34 shows that the bolometer voltage cannot be increased indefinitely. Experimental extension of the curves shows that the above maximum voltage dV/dI becomes negative. This negative dV/dI region is an "unstable" one which allows the bolometer temperature to increase to the burning out point if the attempt is made to increase V above its maximum value. This may be avoided by a ballast resistor placed in series.

If the only noise into the input of the amplifier is considered to be due to thermal agitation, the ENI to be expected from a bolometer and circuit may be computed from equations (17) and (23).

$$\text{Noise voltage} = 1.22 \times 10^{-10}(R'\Delta f)^{1/2}; \qquad (23)$$

where

$$R' \equiv RF.$$

R' is the resistance of the input circuit as seen from the amplifier, and Δf is the proper pass band width. The result is

$$\text{ENI} = \frac{1.22 \times 10^{-10}(\Delta f/F)^{1/2}T^2}{a\phi(dT/dP)^{1/2}W\beta\Delta T^{1/2}}. \qquad (24)$$

The temperature function $(T^2/\Delta T^{1/2})$ is determined by the operating point and has a minimum value of (1.58×10^4) when T = 99.4 C with $T_0 = 25$ C. Since this ΔT is excessive, it would be better to operate with the ΔT determined by a maximum sensitivity. For $T = 20$ C, $(T^2/\Delta T^{1/2})$ is (2.26×10^4) and decreases slowly to the minimum at $\Delta T \backsimeq 100$ degrees. For No. 1 material, $\beta = 3900$ K, and ΔT, for maximum s, is 19.7 C. It is seen, therefore, that for bolometers with $\beta = 3900$ K, the minimum equivalent noise input will not be much smaller (3 db at most) than the value of the ENI given by equation (24) for the operating point which gives maximum sensitivity. The minimum equivalent noise input is, therefore, given practically by

$$\text{MENI} = \frac{1.22 \times 10^{-10}(\Delta f/FW)^{1/2}}{a\phi(dT/dP)^{1/2}}\left[\frac{T^2}{\beta\Delta T^{1/2}}\right]_3 \qquad (25)$$

with $T = T_0^2/(\beta + 2T_0)$. The bracketed quantity is a function of β and T_0 only.

Equation (25) gives a good picture of the way in which the bolometer (and amplifier) characteristics affect the MENI. It is seen from (25) that the resistance of the bolometer is contained only in the factor F, hence it affects the MENI only if it should be such as to make the input circuit values impractical for F approaching unity or if it should impair the design of an amplifier which reaches the noise limit set by equation (23). Equation (25) separates the amplifier circuit design characteristics $(\Delta f/FW)^{1/2}$, the bolometer material characteristics $[T^2/\beta\Delta T^{1/2}]$, and the absorptivity, backing, and flake size characteristics, $a\phi(dT/dP)^{1/2}$.

The values of MENI obtained from equation (25) for the bolometers operating in the 5-μ to 14-μ region in the input circuit shown in Figure 32 are given in Table 14, along with other properties of these 3 instruments. These were computed to be a measure of the d-c heat power before chopping into a 15-cycle square wave. The measured ENI values were not obtained with the voltage adjusted for maximum sensitivity, but are representative of the values obtained at lower sensitivities. Using equation (24) to obtain the value of the ENI under the operating conditions for which the measured value of S–19 was obtained, it is found that the ENI is 0.002 μw. This is in fair agreement with the 0.004-μw experimental value.

TABLE 14. Collected characteristics of BTL bolometers.

	S–19	S–20	XB–108
Backing *	Glass	Quartz	Air
Area,* cm²	6.02×10^{-3}	6.25×10^{-3}	5.79×10^{-3}
R_0 megohms, 25 C	3.93	3.68	3.92
β, degrees K	3390	3369	3430
dT/dP, degrees C/watt	678	275	5270
τ milliseconds	5.9 *	3.1*	135
$(a_{2\mu})$	0.64	0.87	0.72
$a_{5\mu\ 15\mu}$	0.53	0.66	0.23
$s]^{15\,c}_{100\,v}$	350	154	372
Max $s]^{15\,c}$	675	450	270
ENI, μw, d-c, chopped, 15 c (measured)	0.004	0.009	0.008
V for above ENI	202	208	75
V for max s	242	366	86.5
ϕ, 15 c	0.257	0.226	0.079
MENI, 15 c [eq. (8)] μw	0.0025	0.0033	0.0072
F	0.111	0.098	0.117

* Data furnished by BTL from Table 13.

The expression for the final steady-state sensitivity has been quite rigorously derived in the appendix of the final report [12] on thermistor bolometer development under Contract OEMsr–636. It has the form

$$s = \frac{V_b\alpha_b FWaM}{C} \text{ volts per watt,} \qquad (26)$$

where s = final steady-state sensitivity;
V_b = voltage across the bolometer;
$\alpha_b = -\beta/T_b^2$;
F = bridge factor $= Rs/(R_b + R_s)$ where
R_s = balancing resistor;
W = waveform factor;
a = absorptivity;
C = heat dissipation constant;
M = factor which takes into account the change in resistance of the balancing resistance in the bridge if it is an equal thermistor, or the effect of the balancing resistor if it is a metal.

The factor M takes a different form for each of the two cases:

1. If the balancing resistor R_s is of thermistor material and is identical with the bolometer, the

unbalance of the bridge circuit will cause changes in temperature, resistance, and current in this resistor. For this case

$$M = \frac{1}{1 - \alpha_b (T_b - T_0)}. \qquad (27)$$

2. If the balancing resistor R_s is not necessarily equal to R_b and is of metal and has $\alpha_s = 0$, the current and resistance changes produce an M factor of the following form:

$$M = \frac{1}{1 - \alpha_b (T_b - T_0) \dfrac{R_s - R_b}{R_s + R_b}}. \qquad (28)$$

Equation (15) reduces to equation (26) for the final steady-state sensitivity by putting ϕ, the frequency factor, and W, the waveform factor, equal to unity. Equation (15) is for the simplified case which presumes $M = 1$. This approximation is in most cases sufficiently good.

Figure 43 shows a plot of equation (26), with M for the case of the thermistor balancing resistor, with sensitivity as ordinates, and V_b, the bolometer voltage, as abscissa. Values of $T_b - T_0$ are listed on the solid curve. Figure 43 also shows a dashed curve which is computed on the simplifying assumption that M is unity. The reason this curve deviates from a straight line is that α_b decreases as T_b increases.

The same equation plotted with M for the condition of a metallic resistor is shown in Figure 44. Four curves are shown for various values of R_s/R_b. When this ratio is very small, the steady-state sensitivity rises very rapidly as V_b increases to V_p, the peak value, and continues to rise beyond the value corresponding to the peak voltage even though V_b decreases again.

It is also shown in the appendix of the report on thermistor bolometer development [12] that the expression for the time constant, τ, of the bolometer contains the M factor as a multiplier, and that

$$\tau = \frac{H}{C_b} M, \qquad (29)$$

where H = effective heat capacity of bolometer;
C_b = heat dissipation constant;
M = values given by equations (27) or (28).

8.8 OTHER BOLOMETERS TESTED BY SECTION 16.4

8.8.1 The Felix Bolometer

Four bolometers, numbers 2A, 11A, 15, and 19, developed by the Heat Research Laboratory of the Massachusetts Institute of Technology under Con-

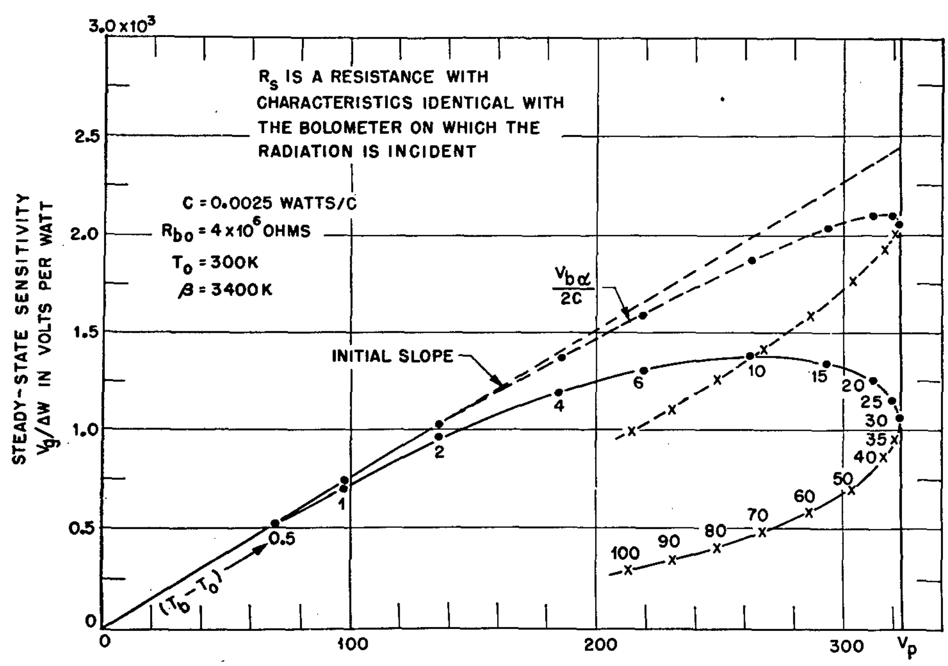


FIGURE 43. Graph showing steady-state sensitivity of BTL bolometer plotted as function of V_b where compensating resistor is another thermistor.

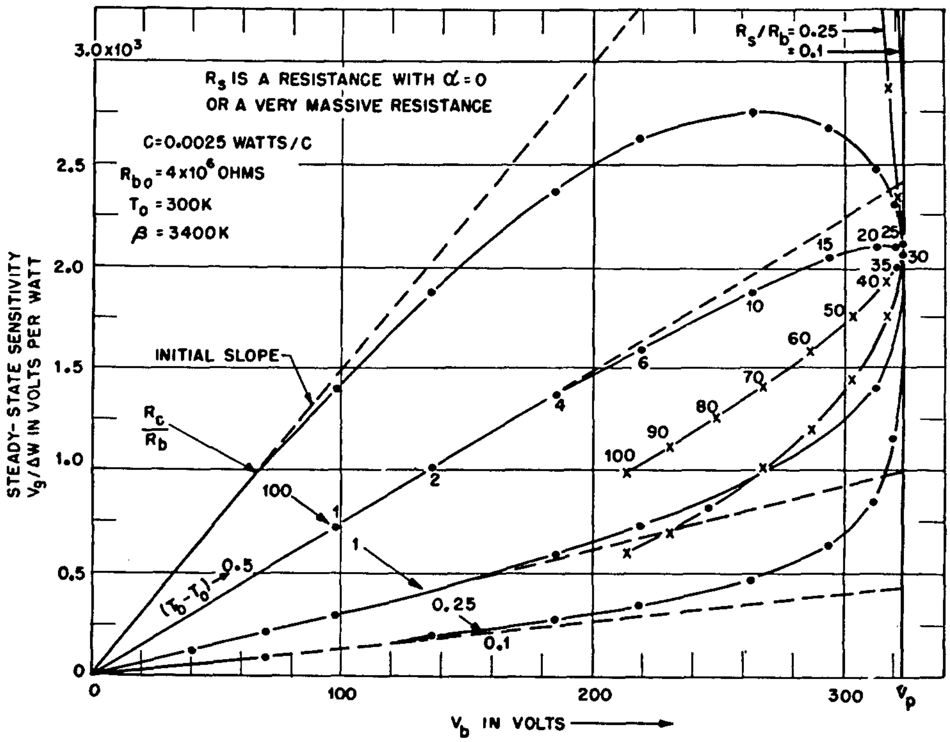


FIGURE 44. Graph showing steady-state sensitivity of BTL bolometer plotted as function of V_b where compensating resistor is a metallic one.

tract NDCrc-180, were sent to Ohio State University under Contract OEMsr-1168 for test purposes. These bolometers, of identical design, are composed of four blackened nickel strips connected in series and mounted close together and parallel in a small cylindrical holder. The electrical leads are sealed into the back slightly above the diameter; the front is covered with a hemispherical silver chloride window. The whole unit is about 1x1 centimeter and is sealed with a filling of hydrogen at a pressure of 4 millimeters of mercury. The bolometers have a total resistance of about 16 ohms and are operated at 1.7 volts across the whole unit. While the elements are rectangular strips, they are masked so that the receiver area of 0.172 square centimeter is circular. The blacking material on No. 2A and No. 15 is aluminum black; on No. 11A and No. 19 it is gold black.

Static Characteristics. The resistance of the bolometers, measured with a Wheatstone bridge while the temperature was varied from 50 to 25 degrees C, was linear, and, from the slope of the curve, the temperature coefficient of resistance α was obtained. The values of α are listed in Table 15.

The variation of the bolometer resistance R_b with d-c electric power input to the bolometer was measured with the Wheatstone bridge circuit, the power into the bolometer being varied by varying the voltage supply to the bridge. Curves showing the variations of R_b with E_b, the voltage across the bolometer, with I_b, the current through the bolometer, and with P, the electric power expended in the bolometer, may be found in Figures 13 and 14 of OSRD Report 5992.[2] The slopes, dR_b/dP, for the bolometers are listed in Table 15.

As in the case of the Strong bolometer, not all the heat power is effective in producing resistance change, nor are all wavelengths necessarily equally effective. Direct measurements (cf. Section 8.4) were, therefore, made to determine the change in resistance of the strip per watt of incident heat power, dR_b/dH, of a known wavelength. The absorptivity, a_λ, was then obtained as the ratio $(dR_b/dH)/(dR_b/dP)$. The values of dR_b/dH and a for the bolometers are tabulated in Table 15.

The spectral response was obtained from 1.0 μ to 14.0 μ for all bolometers. Curves 1 and 2 in Figure 45 show the response, relative to the response of the Coblentz thermopile, of the No. 11A unit adjusted to an absorptivity of 0.42 at 2.0 μ. Curve 1 was

TABLE 15. Values of various constants for the Felix bolometers.

Constant	Units	No. 2A (Al black)	No. 15 (Al black)	No. 11A (Au black)	No. 19 (Au black)
α	Per degrees C	0.00366	0.00299	0.00330	0.00396
dR_b/dH	Ohms per watt	10.3	13.3	10.7	21.2
dR_b/dP	Ohms per watt	16.25	15.5	25.4	28.2
dR_b/dT	Ohms per degree C	0.0384	0.040	0.0341	0.046
dT/dP	Degrees C per watt	424.	388.	732.	613.
$a_{2\,\mu}$	Absorptivity	0.64	0.85	0.42	0.75
$a_{5\mu-14\,\mu}$	Absorptivity	0.64	0.45	0.15	0.65
Center-strips	Milliseconds	20.2	21.4	21.8	19.0
ENI (14.6 c)	μw, 5 μ to 14 μ	0.02	0.03	0.05	0.01
ENI (27.6 c)	μw, 5 μ to 14 μ	0.04	0.03	0.11	0.02
MENI (14.6 c)	μw, 5 μ to 14 μ	0.002	0.003	0.005	0.001
MENI (27.6 c)	μw, 5 μ to 14 μ	0.005	0.01	0.02	0.004
Minimum detectable signal (27.6 c)	μw, 5 μ to 14 μ	0.04	0.10	0.12	0.015

obtained when one of the edge elements was illuminated and curve 2 when one of the central elements was illuminated, indicating that the response is better by a factor of about 2 from 6 μ to 14 μ for

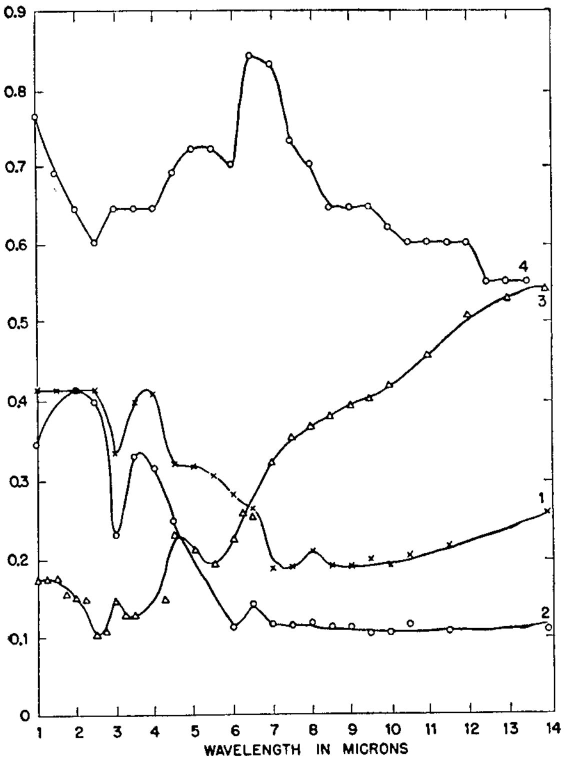


FIGURE 45. Absorptivity curves for Felix bolometers.

edge-strip than for central-strip illumination. Curve 4 in Figure 45 shows the relative spectral response of bolometer No. 2A with respect to the Coblentz thermopile throughout the 1.0-μ to 14.0-μ region. The absorptivity of No. 2A is approximately 0.64 throughout, and the curve is adjusted to this value at 2.0 μ.

Bolometer No. 2A was exposed to sunlight, and the silver chloride window became blackened to visible light. After this had occurred, its spectral response was again determined from 1.0 μ to 14.0 μ, and curve 3 in Figure 45 shows the response relative to the Coblentz thermopile after it had been

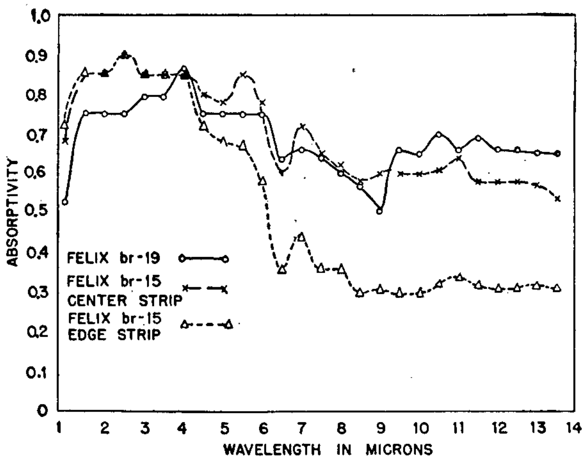


FIGURE 46. Absorptivity curves for Felix bolometers.

exposed. The curve is adjusted to an absorptivity of 0.15 at 2.0 μ. It may be seen from curves 3 and 4 that from 1 μ to about 7 μ the absorptivity is less than 50 per cent of the value before it was exposed. In the atmospheric window region, 8 μ to 14 μ, the absorptivity, though smaller than in the unexposed state, is everywhere more than 50 per cent of the original absorptivity.

Figure 46 shows the absorptivity curves for bolometers No. 15 and No. 19 adjusted to the respec-

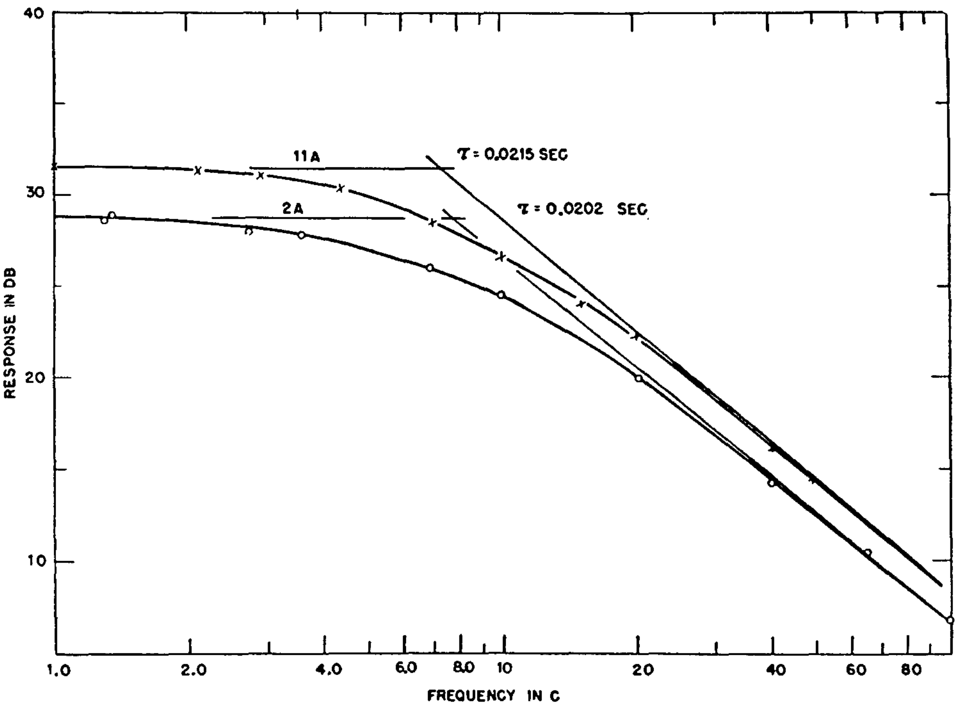


FIGURE 47. Frequency-response curves for Felix bolometers.

tive values 0.86 and 0.75 at 2.0 μ, at which wavelength a direct measurement was made.

Dynamic Characteristics. The frequency response and time constant for each bolometer were determined from 1 to 100 c. The experimental curves for

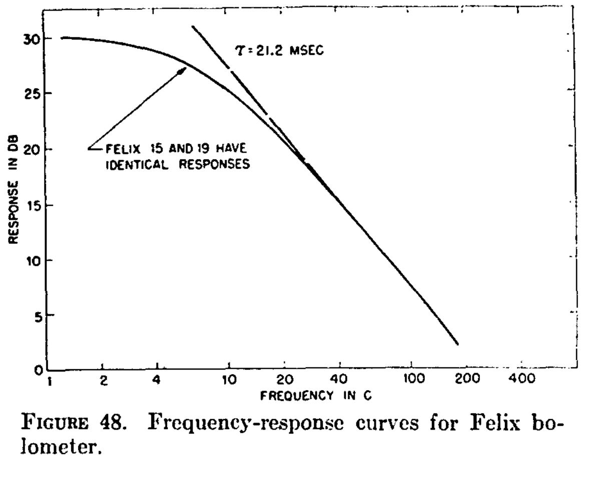


FIGURE 48. Frequency-response curves for Felix bolometer.

all the bolometers approximate very closely the type of curve to be expected if a time constant for the bolometer exists. Figures 47 and 48 show the frequency-response curves for the Felix bolometers. The time constants are listed in Table 15.

It was observed, however, that each of the four strips of the Felix bolometer appeared to possess its own individual time constant. Table VI of OSRD Report 5992[2] lists the values of τ, determined by the parallelogram method, for each strip of all the bolometers.

The ENI and MENI for these bolometers were determined at the frequencies 14.6 and 27.6 c, and Table 15 lists the values found.

By the method described earlier, the *minimum detectable signal* [MDS] (see Section 8.3.4) for the bolometers was obtained. A record showing both signal and noise on the same chart for signals above the noise is shown in Figure 7. The values of the MDS determined from such charts are found in Table 15.

From the static characteristics and frequency response of the bolometers and the amplifier gain characteristics, the output voltage per watt of heat power input was calculated. These predicted values were compared with the observed outputs and the results of the comparison are listed in Table 16. The largest difference between observed and predicted values is less than 2 db and in most cases is about 0.5 db. This is good agreement. The agreement is considerably better than in the case of the

Strong bolometer. This can probably be explained by improvements in measuring technique made during the interval between the two sets of measurements. It was not possible to remeasure the Strong bolometer with the improved technique, because an element had burned out.

TABLE 16. Table showing the expected output compared with the measured output for radiation in the 5-μ to 14-μ region.

	No. 2A	No. 15	No. 11A	No. 19
Volts/μw observed, 14.6 c	19.0	11.4	4.95	25.9
Volts/μw expected, 14.6 c	18.5	12.2	6.13	26.3
Difference (db)	0.2	0.52	1.8	0.2
Volts/μw observed, 27.6 c	6.1	4.05	1.8	9.4
Volts/μw expected, 27.6 c	5.87	3.8	1.9	8.5
Difference (db)	0.3	0.52	0.42	0.85

8.8.2 The Polaroid Evaporated Metal-Strip Bolometer

A number of evaporated nickel bolometers made by the Polaroid Corporation Laboratories under contract with Division 5, NDRC, were submitted for testing. One of these, an evaporated nickel strip, was constructed for Wright Field and designated WF–1. Its unit was about 1x0.5 millimeter, 0.02 μ thick, and was evaporated onto a nitrocellulose film about 0.06 μ to 0.08 μ thick. The resistance of the bolometer was about 15 ohms; its receiving area had a coating of antimony black. Three other bolometers (Nos. Ni324, Ni347, and Ni350) were evaporated onto a nitrocellulose film, in the form of a cross with each leg having an area of about 0.045 square centimeter. Each bolometer was mounted in a cylindrical brass case about 2 centimeters outside diameter and 1 centimeter long, with a silver chloride window covered with a protective coating. Table 17 lists the resistances of Nos. Ni324, Ni347, and Ni350. All four bolometers operate in air at atmospheric pressure.

Static Characteristics. The variation of the bolometer resistance with temperature and with electric power expended was measured by means of a Wheatstone bridge. The resistance variation of one leg when the power into an adjacent leg varied was also measured. Heating one strip obviously produces a measurable temperature rise in the others.

Dynamic Characteristics. The frequency-response characteristics of the bolometers were measured from 1 to 400 c and are shown in Figure 49. Only WF–1 had a time constant of value 4.7 milliseconds. The other three frequency-response curves did not

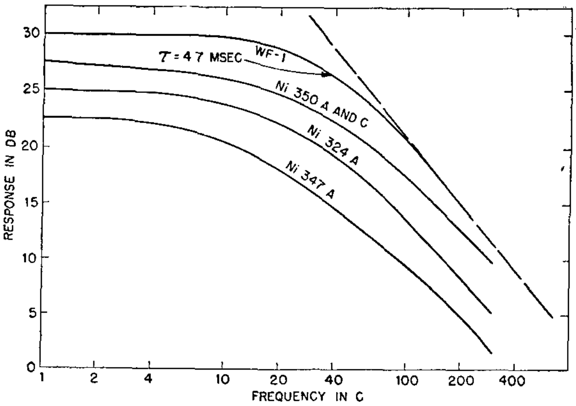


FIGURE 49. Frequency-response curves for Polaroid bolometers.

warrant a computation of the time constant. Legs A and C of No. Ni350 were identical in response, so characteristics of only leg A of Nos. Ni347 and Ni324 were measured. All frequency-response curves have about the same shape.

TABLE 17. Static characteristics for the Polaroid bolometers.

Bolometer	Leg	dR/dP (ohms/watt)	R (ohms)	dR/dT (ohms per degree C)	$\alpha = 30$ C (per degree C)
No. Ni324	A	119	63.6	0.217	0.00168
	C	118	65.0		
	$\frac{dR_{\text{leg A}}}{dP_{\text{leg C}}}$ = approximately 10 ohms/watt				
No. Ni347	A	130	43.2		
	B	132	44.0	0.154	0.00175
	C	130	43.6		
	D	127	44.7		
	$\frac{dR_{\text{leg 1}}}{dP_{\text{leg 2}}}$ = approximately 5 ohms/watt. It does not matter whether leg 1 and leg 2 are adjacent.				
No. Ni350	A	138	132.4		
	B	148	122.1	0.0334	0.00104
	C	153	123.1		
	D	139	133.0		

The ENI was measured for each bolometer, using a tuned amplifier working at 14.6 c with special input transformer furnished by Polaroid. The ENI

values are listed in Table 18. Figure 8 shows an Esterline-Angus recorder trace of signal and noise on the same record for bolometer No. Ni324. The MDS is about 0.015 μw. No spectral response measurement was made on any of the Polaroid bolometers.

TABLE 18. ENI values for the Polaroid bolometers determined with 5-μ to 14-μ radiation.

Polaroid unit	ENI
324	0.01
347	0.01
350	0.02
WF-1	0.02

8.8.3 The Radio Corporation of America [RCA] Bolometer

Two RCA bolometers, No. 18 and No. AX, were sent by the Bureau of Ships to Ohio State University Contract OEMsr–1168 for testing. The elements are made of a tellurium-zinc alloy evaporated onto a nitrocellulose film which is mounted on a plastic base. The operation is in vacuum with a window of silver chloride closing the unit on the front face. The bolometer receiver is in the form of a strip 0.5x1.0 millimeter having a resistance of about 10,000 ohms and a negative temperature coefficient.

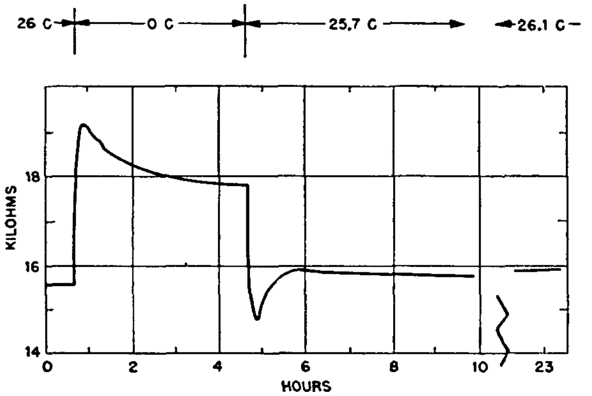


FIGURE 50. The effect of past history on the resistance of the RCA bolometer No. AX.

Static Characteristics. Attempts to measure the temperature dependence of the resistance of these bolometers were not very successful, because the resistance appeared to depend also on the history of the samples. It was therefore not ascertained whether they obeyed the characteristic thermistor relation, $R = R_0 \exp(\beta/T)$. At 26 degrees the temperature coefficient is about 0.009 C for No. 18 and 0.0075 C for No. AX.

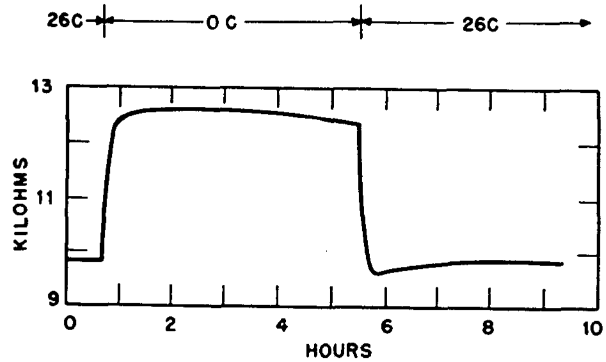


FIGURE 51. The effect of past history on the resistance of the RCA bolometer No. 18.

The nature of the effect of history upon the bolometer resistance is indicated in Figures 50 and 51. In these figures the resistance has been plotted as a function of time, and the temperature of the bolometer is noted. The bolometer was quickly changed from room temperature to about 0 C and later changed back. A rapid temperature change appears to produce a larger resistance change than does a slow one.

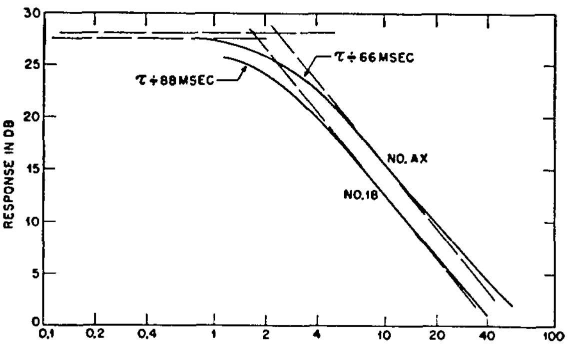


FIGURE 52. Frequency-response curve of the RCA bolometers.

Dynamic Characteristics. The time constants for both bolometers were measured. The frequency-response curves, plotted in decibels versus log frequency, are shown in Figure 52. For clarity the curve for No. AX is displaced an arbitrary amount from that of No. 18. In the region available for measurement, the frequency-response characteristics of the units can apparently be represented by time con-

stants but from Figures 50 and 51 it may be seen that these cannot be effective down to zero frequency. The No. AX unit also deviates slightly from true time-constant behavior above 20 c. The time constants are about 70 milliseconds and 80 milliseconds for No. AX and No. 18 respectively.

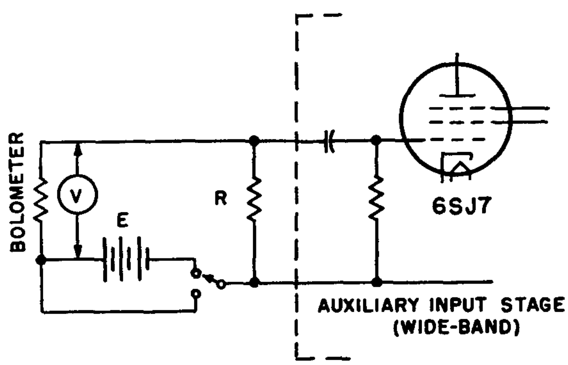


FIGURE 53. Auxiliary input stage used with RCA bolometer.

The ENI values, measured by using the input circuit shown in Figure 53 followed by the tuned amplifier working at 14.6 c, are listed in Table 19. The noise output from the bolometers was several times greater with the bolometer current on than with it off. When no current flowed, the output noise arose in the first tube of the amplifier rather than in the bolometer input circuit. An increase in current, with a larger accompanying voltage, produced an increase in noise voltage as well as in signal voltage. Bolometer voltages up to 5 or 6 volts were tried but resulted in a poorer signal-to-noise ratio than when only 1 volt was applied.

TABLE 19. ENI values for the RCA bolometers determined for 5-μ to 14-μ radiation at 14.6 c.

	Circuit 1		Circuit 2		Circuit 3	
	18	AX	18	AX	18	AX
Amplifier output noise (v)	0.15	0.15	0.8	1.0	0.8	0.6
ENI (μw)	0.02	0.02	0.045	0.05	0.04	0.03
Volts across bolometer	1.2	1.8	3.7	5.4	4.3	6.2

Circuits 1, 2, and 3 referred to in Table 19 mean that in the input circuit of Figure 53 $E = 7.5$ volts, $R = 50{,}000$ ohms wire wound; $E = 45$ volts, $R = 100{,}000$ ohms wire wound; and $E = 45$ volts, $R = 75{,}000$ ohms, respectively. A metalized IRC series resistor was used in each instance. The amplifier output noise, found to be 0.07 volt for all circuits, was determined by replacing the bolometer battery with a short circuit. Because of the difficulty of estimating the noise and because of the apparent variations in the bolometer characteristics, the ENI values are not so reliable as in the cases of the other types of bolometer. It appears also that the larger bolometer voltage with its greater working sensitivity is of no real advantage for the detection of small signals at 14.6 cycles.

Using circuit 1 with the 14.6-cycle tuned amplifier, the value of the Johnson noise would be about 12 db below the measured noise. The MENI is, therefore, about 0.005 μw.

Another indication of the merit of the bolometer may be had from the record reproduced in Figure 10, which shows the magnitude of the noise and of the noise plus signal for a small amount of 5-μ to 14-μ radiation. With a minute of exposure, 0.03 μw may be readily detected.

The spectral response was obtained and is shown in Figure 54. The ratio of the response to that of the Coblentz thermopile has arbitrarily been adjusted to unity at 2.0 μ.

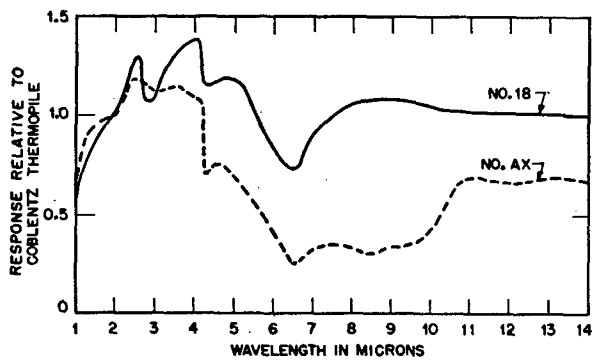


FIGURE 54. Spectral-response curve for RCA bolometer.

8.8.4 The Superconducting Bolometer

Two superconducting bolometers, No. 1 and No. 4, built in the Johns Hopkins laboratories under the supervision of D. H. Andrews, were sent, through arrangements made with Section 16.4, to the Ohio State University Contract OEMsr-1168 by the Bureau of Aeronautics for tests on sensitivity, frequency response, etc.

The cryostats, used to control the operating temperature of the bolometers, are copper cylinders about 1 foot long by 6 inches in diameter, with the

receiver at one end. The detecting element of this bolometer is a strip of columbium nitride with effective dimensions 0.317x0.0254 centimeter, receiving area 0.00808 square centimeter. This strip is cemented to a thin sheet of bakelite which is fastened to a copper block in contact with the liquid hydrogen chamber. A piece of polished rock salt, which transmits radiation from 1 μ to 15 μ, serves as a window. The window makes a vacuum seal with the outer container which must be evacuated before the cooling chambers are filled. From the end opposite the receiving element emerge the electrical connections and the filling tubes. The cooling chambers

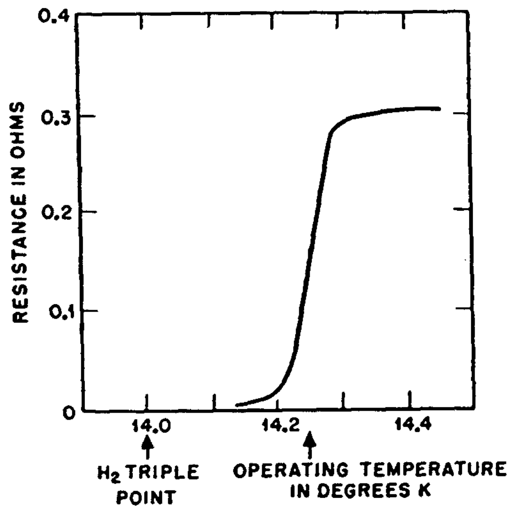


Figure 55. Working temperature region of superconducting bolometer.

are concentric cylinders, the outer one being for liquid nitrogen, and the inner one, of 1.0 liter volume, for liquid hydrogen. A copper block, to which the receiving element is attached, makes good contact with the hydrogen chamber. Around this block is wrapped a heating coil of about 500 ohms, so that the operating temperature of the bolometer may be controlled.

The bolometer becomes sensitive to small heat changes when its temperature is between 14.2 and 14.3 K or slightly above the triple point of hydrogen (see Figure 55). Good insulation to heat from outside the cryostat is provided by the vacuum in the outer container. Liquid nitrogen is forced under pressure from a Dewar flask into the cooling chamber until the nitrogen streams from the exit tube. The hydrogen chamber is then precooled by partially filling it with nitrogen, which is blown out before the hydrogen is admitted.

The input circuit used is shown in Figure 56. The leads from the heater coil, the bolometer, and a dummy resistance emerge from the back of the cryostat and lead to the input circuit as shown. The complete input circuit was shielded in a metal chassis. Two potentiometers, P_1 and P_2, and switch, S_1, provide control of the heater current.

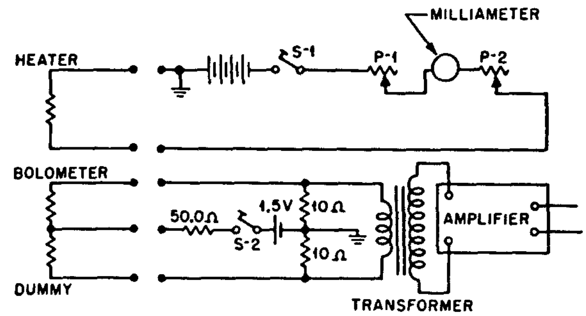


Figure 56. Input circuit for superconducting bolometer.

Static Characteristics. No measurements were made on α, the temperature coefficient of resistance, or on dR/dP, the rate of change of R with electric power, or on the absorptivity.

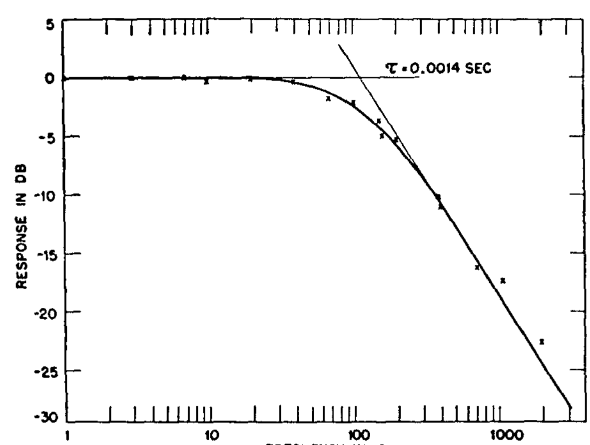


Figure 57. Frequency-response curve for superconducting bolometer.

Dynamic Characteristics. The frequency response of cryostats No. 1 and No. 4 was measured from 1 to 400 cycles and from 1 to 2,000 cycles respectively.

Figure 57 shows the frequency response of bolometer No. 4. The curve is that which would be expected if the instrument had a time constant of 1.4

millisecond. As the frequency response for No. 1 is that which would be expected if it had a time constant of 1.8 millisecond, the curve is not shown. Although their physical sizes are comparable, the time constants of the two bolometers are smaller than the time constants of most of the other bolometers tested by a factor of about 10, and are smaller than the quoted time constants of the BTL thermistors by a factor of about 2.

The ENI values were determined for both No. 1 and No. 4 at 14.6 cycles and 27.6 cycles with a tuned amplifier, and at 20 cycles and 14.6 cycles, respectively, using a wide pass band amplifier. Table 20 gives the ENI values for both bolometers under the various conditions.

Figure 11 shows an Esterline-Angus record made to determine the MDS at 27.6 cycles for the cryostat bolometers. For No. 1 the MDS was 0.0005 μw, and for No. 4 it was 0.0006 μw.

The spectral response of the two was compared with the response of the Coblentz thermopile which has been used as a standard in previous measurements. In Figure 58 are given curves showing the relative response arbitrarily adjusted to unity at 2.0 μ where the glower has its peak. It may be seen that from 1 μ to 6 μ the responses are about the same, but from 6 μ to 14 μ these bolometers appear to become gradually blacker than they were at 2 μ.

TABLE 20. ENI values for the cryostat bolometers for 5-μ to 14-μ radiation.

Bolometer	ENI (μw) 14.6 c	ENI (μw) 27.6 c	ENI (μw) wide-band amplifier
1	0.0006	0.00035	0.019 (20 c)
4	0.0015	0.0006	0.024 (14.6 c)

The measurements reported above show that the cryostat bolometer is more sensitive by a factor of about 10 than any other device tested under Contract OEMsr-1168. It has, in addition to its high sensitivity, a small time constant and it appears to be quite black throughout the whole spectrum.

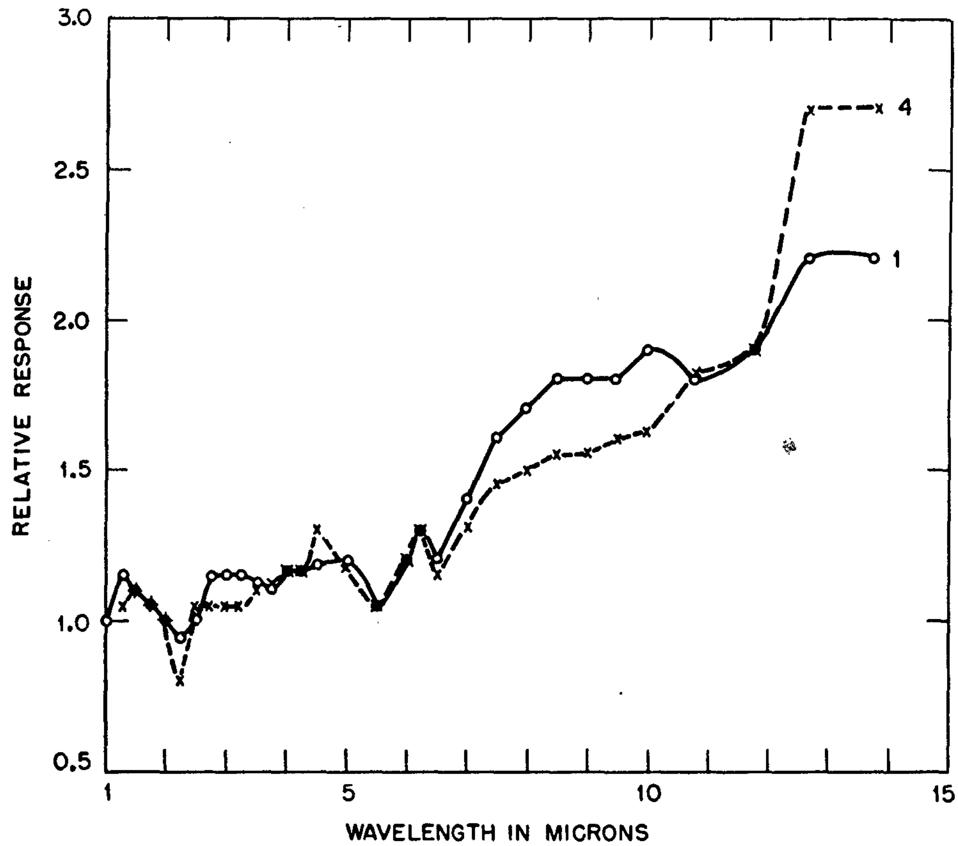


FIGURE 58. Spectral-response curve for superconducting bolometer.

8.8.5 The Donau Gerät Bolometer

One Donau Gerät evaporated metal-strip bolometer was received from Section 16.4, NDRC, and two from the Engineer Board, Fort Belvoir, Virginia, for testing. For easy reference they were numbered and described in the following manner:

No. 1 in glass case equipped with window, rotating shutter and cable; 65 ohms per strip.

No. 2 in glass case equipped with window; 950 ohms per strip, worthless as a heat detector.

No. 3 without case or window; 90 ohms per strip, one strip defective.

The bolometers are apparently made of metal, without backing, evaporated onto a thin film of nitrocellulose. There are two strips set parallel with each other, with all four end leads available. The nitrocellulose skin bearing the bolometers is stretched on a plastic frame across a hole in the center of the frame. The unit is fitted into a glass tube into which the four leads are sealed. The window is a circular plate of a mixture of thallous bromide and thallous iodide said to transmit radiation fairly well out to 40 μ. As the leads are sealed into the glass and the window is sealed to the tube containing the bolometer, it is presumed that the unit operates at reduced pressure, perhaps with some gas other than air.

Static Characteristics. The values of the static characteristics of the Donau Gerät bolometers, dR/dT, α, and dR/dP are grouped in Table 21.

TABLE 21. Static characteristics of the Donau Gerät bolometers.

Bolometer	dR/dT (ohms/degree C)	α/degree C	dR/dP (ohms/watt)
1	0.116	0.00195	153
3	0.130	0.00130	155

Dynamic Characteristics. Frequency-response curves, over the range 1 to 150 c, were found for bolometers No. 1 and No. 3, as shown in Figure 59. It may be seen that the curve for No. 1 approximates that for a time constant of 10.9 milliseconds, while the curve for No. 3 is quite different. It should be recalled that No. 1 is enclosed and presumably operating at somewhat less than atmospheric pressure, while No. 3 is not enclosed.

The ENI for bolometer No. 1, operated at 2.0 volts in the tuned amplifier, was 0.051 μw peak to peak at 14.6 cycles and 0.113 μw peak to peak at 27.6 c.

The Johnson noise should have been smaller than the observed noise by 26 db for the 14.6-c measurement and 20 db for the 27.6-c measurement. If the amplifier noise and current noise were eliminated, the value of the MENI would be about 0.003 μw and 0.011 μw at the two frequencies respectively. No spectral-response curve was made.

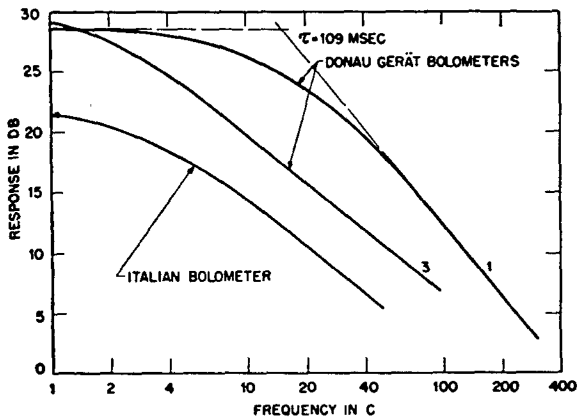


FIGURE 59. Frequency-response curves for Donau Gerät bolometer and Italian bolometer.

8.8.6 The Italian Bolometer

Two bolometers of Italian make were sent to Ohio State University through Section 16.4, NDRC. One was received broken; the present remarks concern only the other. The bolometer is a thin metal strip having a resistance of about 280 ohms, supported on a nitrocellulose film, and enclosed in a brass case with a rock salt window. The case is apparently connected to one end of the bolometer, and the other lead emerges through a fiber insulator. In one end is soldered a tube which is presumably for evacuation, but the bolometer was not evacuated for the tests described. The metal strip had a very wrinkled appearance. Its linear dimensions are 4x5 millimeters, giving an area of 0.2 square centimeter. No information was furnished concerning its recommended operating voltage.

Static Characteristics. The value of dR/dT was found to be about —0.35 ohm per degree C, and the value of dR/dP to be about —200 ohms per watt. It was found to be very difficult to make good resistance measurements on this bolometer, probably because of the poor contacts provided by its crinkly surface.

Dynamic Characteristics. The frequency response from about 2.5 to about 40 c is shown, as obtained with a General Motors amplifier, by the curve of Figure 59. No measurement of ENI was made as no signal above noise could be discerned with the largest available calibrated heat input (69 μw per square centimeter).

8.9 OTHER HEAT-SENSITIVE DEVICES

8.9.1 The Golay Heat Detector [16]

Three separate Golay units were investigated under OEMsr–1168. The first was a unit loaned by the Signal Corps Laboratories at Eatontown, New Jersey. The other two units were more recent models built by Don Lee, Incorporated, for Naval Aeronautics Modification Unit (NAMU) at Johnsville, Pennsylvania, and furnished for test by the Bureau of Aeronautics, Navy Department. These units will hereafter be referred to respectively as *a*, 1, and 2.

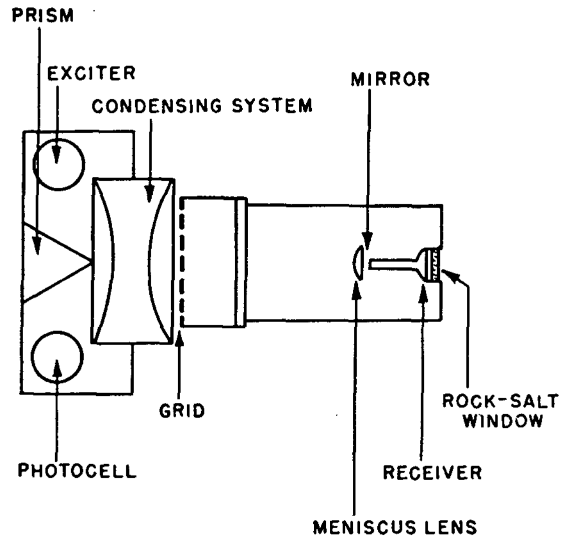


FIGURE 60. Schematic diagram of Golay cell.

The Golay heat detector is shown schematically in Figure 60. Its operation has been described in Section 8.2.3. The photocell circuit which is part of the unit is shown in Figure 61. A cathode-follower circuit was introduced between the photocell and the amplifier, which reduced the impedance of the photocell circuit to a 50,000-ohm output. This permits the use of a cable from the detecting device to the amplifier and also allows the detecting device to be at some distance from the signal observing post.

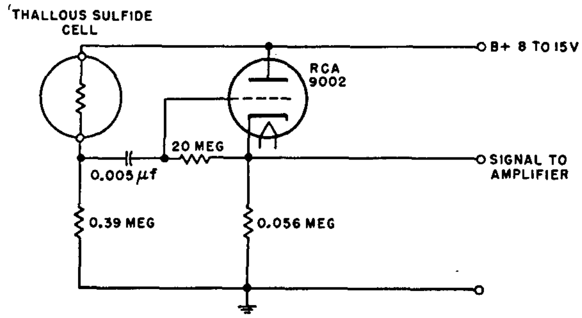


FIGURE 61. Input circuit of Golay detector.

The Golay device must always be operated with intermittent illumination; in fact, the construction is such that at zero frequency it gives zero response.

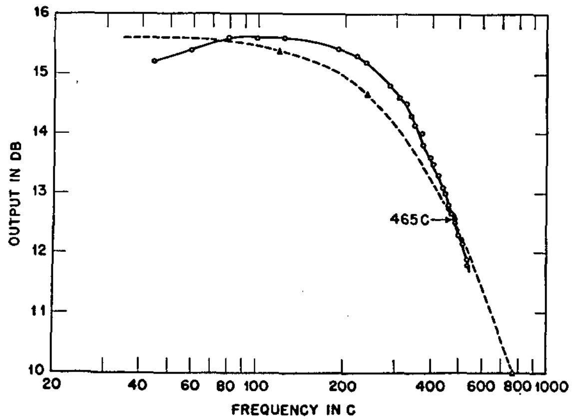


FIGURE 62. Frequency-response curve of the Golay detector.

Measurements on the frequency response of these instruments showed that in no case can a time constant be ascribed. The first unit (*a*) was found to give a maximum response when operated near 140 c. The frequency-response curve is shown in Figure 62. Corresponding curves for the later models (1 and 2) are shown in Figure 63 and indicate that maximum

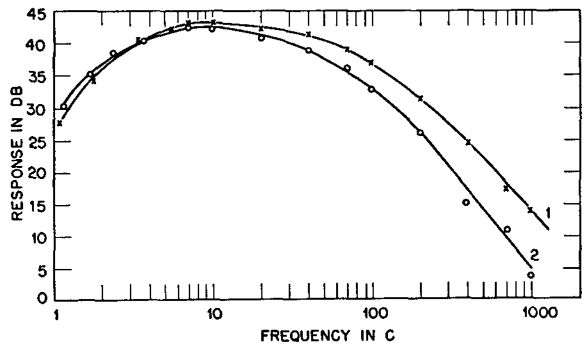


FIGURE 63. Frequency-response curves of Golay detectors 1 and 2.

response would be obtained when operated near 10 c.

The ENI values were obtained for all three units, the first at a frequency of 140 c and the others at 14.6 c. The values are given in Table 22.

TABLE 22. ENI values for the Golay heat detectors determined for radiation in 5-μ to 14-μ region.

Bolometer	ENI (14.6 c)	ENI (140 c)	Area of receiver
a	...	0.010 μw	0.01 sq cm
1	0.0025 μw	...	0.071 sq cm
2	0.0014 μw	...	0.071 sq cm

The spectral response of these detecting elements was investigated in the usual manner, and it was found that the receiving elements were uniformly black throughout the spectral region 1 μ to 14 μ.

It may be seen from the foregoing that Golay detectors may be produced which have an extremely rapid response, but at the same time maintain very low ENI values.

8.10 COMPARISON OF THE DETECTORS

8.10.1 Basis of Comparison

In the foregoing sections of this chapter the construction details and performance characteristics of the various detectors developed in Section 16.4 and elsewhere and tested under Contract OEMsr-1168 have been discussed in detail. It is the purpose of this section to compare these characteristics so that some estimate of their relative merit may be had. Certain of these characteristics may be singled out to form the basis of this comparison. It is assumed that the primary interest in these detectors is in their military applications. As most military objectives are at a temperature which is different from the background by only a few degrees, it is important that the detectors be capable of detecting exceedingly small amounts of radiant power above the noise background, that they have sufficiently good response at high frequencies to permit rapid scanning, and that their response to radiation be high at least in the window region (8 μ to 14 μ).

The quantities measured relating to the above requirements are the ENI, the frequency response, and the spectral response. It must be recalled that the ENI is dependent on a number of factors. Ideally the amplifier used with these detectors should be noiseless so that it should be possible to work down to the noise threshold of the detector itself. The lowest output value of the noise would be the amplified Johnson noise of the detector. It is supposed that there are no microphonic or current noises associated with the detector. It was found impossible in any instance to work down to the limit of the Johnson noise because of noises originating in the amplifier. In some cases, current noises were quite significant. On the other hand microphonic noises, in general, contributed very little to the total noise output. It did not seem expedient to attempt to build an amplifier with less noise than the one described under "Amplifiers," Section 8.4. Except in cases where current noises were significant, the measured noise output of the tuned amplifier when the detectors were in the circuit was about the same for all detectors for all frequencies of operation. The measured ENI is, therefore, not as good a method of comparison as it could have been if it had been possible to work down to the Johnson noise.

From the time-constant or the frequency-response curve, it can be seen how the response changes with the frequency of interruption of the radiation. One of the primary requirements from a military point of view is the ability to obtain a great deal of information in a short time. A detector with a fast response is, therefore, of greater use than one with a slow response, everything else being equal.

As has been pointed out, not all the heat which falls on a detector is utilized in producing a response. This is borne out by the cases in which the ENI measured at long wavelengths is poorer than the measured ENI for 2-μ radiation. It is, in general, true that the more uniformly black the detector the more useful it is. It may be possible to increase the response if the blacking is improved.

Because of the experimental difficulties attached to the ENI measurements, the zero-frequency responsivity together with the frequency response might also be used as a basis for comparison. The responsivity in volts per watt was determined from curves such as are found in Figure 5, the gain of the amplifier, and the frequency response. The rms volts output is well above the noise and its value per watt of heat input peake-to-peak square wave may be read directly from the curve. When the volts per watt value, read from the curve, is divided

by the amplifier gain and corrected for waveform and frequency fall-off, the responsivity in volts rms per watt rms into the amplifier is obtained. In comparing the detectors in this way it must also be remembered that their usefulness depends on the noise inherent in them. If noiseless amplifiers of equal gain and noise pass band were used for all the detectors, the comparative noise output would be proportional to the square root of the ratio of the resistances. It might, therefore, be thought that for two detectors with the same zero-frequency responsivity used with noiseless amplifiers of equal gain and noise pass band, the one with the shorter time constant would be the more useful. This might not be true, however, because if the resistance of one were considerably larger than that of the other the noise output for it would be greater than for the other. It would, therefore, not be possible to detect such small signals before reaching the noise, or the ENI would be poorer.

The above remarks are general and are introduced because it is difficult to compare on fair and equal bases a large number of devices of as great design diversity as those described in this chapter. Great caution must, therefore, be used with any table in which performance characteristics are compared. The information given in Table 23 is the result of measurements made under Contract OEMsr–1168 on certain detectors and probably cannot be used to generalize upon others of the same type.

In view of the preceding remarks certain information on the best device of any particular group tested has been assembled in Table 23. Where only one unit of a type was on hand, as for example the Strong bolometer, the values for it are quoted. For information on any of the other examples, reference should be made to the appropriate section of this chapter. The detectors are listed in the order of increasing ENI at 15 c, using radiation predominantly in the 5-μ to 14-μ region. Where two units have almost identical ENI, the one with the shorter time constant, or flatter frequency response, is rated higher. For each case listed in Table 23, the frequency at which the response is down 6 db (a factor of 2) from the response at 15 c is listed. Reference should be made to the frequency-response curve in the cases where no time constant is listed. Also listed are the spectral response, the responsivity in volts per watt at zero frequency, the resistance in ohms, the volts across the detector in operation, and the area in square centimeters. As the Golay device produces a voltage only when the heat cell is used in conjunction with a photocell and cathode-follower circuit, the responsivity listed for it must be thought of as the responsivity of the cell plus the photocell and the follower circuit.

TABLE 23. Comparative values for various detectors.

	ENI (μw at 15 c)	τ (milliseconds)	Freqency at which responsivity is down 6 db from 15 c	Spectral response in 1μ to 14μ	Responsivity volts/watt zero frequency	Resistance in ohms	Volts across detector	Area in sq cm
Cryostat No. 1 bolometer	0.0006	1.8	145	Uniform	9.77	0.3	0.003	0.00808
Golay No. 2 heat detector	0.0014	....	72	Uniform	3,440.0*	....	....	0.071
BTL S-19 bolometer †	0.004	....	58	Poor from 3.5μ to 6.5μ	2,700.0	2.7×10^6	202.0	0.00602
Polaroid Ni324 bolometer	0.01	....	60	....	2.0	64.0	0.96	0.045
Felix No. 19 bolometer	0.01	19.0	33	Uniform	2.0	16.0	1.7	0.172
Strong bolometer †	0.03	....	47	Uniform	0.3	4.0	0.96	0.057
RCA No. 18 bolometer	0.02	80.0	30	Uniform	....	9,800.0	1.2	0.005
Schwarz P4772/9 thermopile	0.04	....	40	Cuts off at 10	0.72	23.0	0.0	0.04
Harris thermopile †	0.20	....	39	Uniform	0.364	100.0	0.0	0.11
Weyrich thermopile	....	66.0	37	Uniform	0.29	10	0.0	0.02
Eppley thermopile	....	90.0	28	Uniform	0.375	5.8	0.0	0.01

* Responsivity measured at the output of the cathode-follower circuit shown in Figure 61.
† Developed by Section 16.4.

8.11 RÉSUMÉ

The development of infrared detectors during the war period may be summarized briefly in the following manner. The development has been essentially in the field of thermopiles and bolometers. In the case of the former, the improvement is not phenomenal. Under Section 16.4, the Harris thermopile was developed which has very much the same responsivity as thermocouples of the past but is somewhat more rapid-acting. The Eppley thermopile is very nearly equivalent to the well-known Weyrich unit used so extensively in spectrographic work. Both of the above are undoubtedly more rugged in character than the Weyrich type. The Schwarz thermopile developed in the Hilger laboratory may be regarded as a definite step forward in thermopile construction. The actual responsivity is roughly twice that of one of the former types. The Schwarz thermopile has the disadvantage of being easily broken.

The greatest effort has been expended in the development of bolometers. Although well known, these were used only very seldom in the prewar era. Many variations of bolometers have been designed, but they fall essentially into two categories, the low-impedance and the high-impedance types.

Examples of the low-impedance types are the Strong nickel-strip and the so-called Felix bolometer. The first of these was developed entirely under Section 16.4 and the second at least in part. Other low-impedance bolometers are the superconducting unit developed by Andrews and the Polaroid unit. The RCA instrument is of intermediate impedance. The BTL bolometer is a high-impedance unit developed under Section 16.4.

A third development is the Golay cell, which is an outgrowth of the Hayes cell. This device has been greatly improved in sensitivity and by the introduction of ballast cells was made nonmicrophonic.

The most sensitive of all the detectors developed is the superconducting bolometer worked out by Andrews which has an inherent noise level, so low that its ENI is only 6×10^{-4} μw when operated at 15 c with a tuned amplifier of 2-c bandwidth. A rather close second is the Golay cell, for which a signal of 1.4×10^{-3} μw is equivalent to the noise of the instrument when operated under conditions equivalent to the foregoing. The other bolometers, when operated under similar conditions, are roughly equivalent to each other, all having equivalent noise inputs of about 10^{-2} μw. A slight edge might be given to the BTL bolometers, of which one was found to have an ENI as low as 4×10^{-3} μw.

The superconducting bolometer and the Golay cell are about an order of magnitude better than any of the other detectors developed, the latter being only slightly better than prewar bolometers. The real advance has been in the improvement in frequency response to the point where a-c amplifiers might advantageously be employed. The use of a-c amplifiers virtually eliminates thermal drafts from the detecting system.

Chapter 9

FAR INFRARED RECEIVING SYSTEMS FOR MILITARY APPLICATIONS

By *Alvin H. Nielsen* [a] and *Harald H. Nielsen* [b]

9.1 INTRODUCTION

9.1.1 Types of Military Application

All bodies at temperatures above absolute zero emit electromagnetic radiations with wavelengths in the infrared. Because most military installations, industrial centers, ship convoys, etc., are hotter than their surroundings, detection of them by means of the self-emitted infrared radiations immediately suggests itself. The advantages of the method, namely that the detecting device does not betray its own position and that the heat energy emitted by military equipment lies principally in the wavelength interval or 8 to 14 μ, which is not seriously attenuated by the atmosphere, suggest the importance of developing infrared devices for the following purposes:

1. To detect personnel on foot or in small boats or landing craft.
2. For mounting on the ground or in aircraft for the detection of tanks or other vehicles.
3. For mounting on land to detect aircraft.
4. For mounting in planes to detect industrial centers, factories, or concentrations of military matériel in order to determine suitable targets for manual bombing or for attack with heat-homing bombs.
5. For mounting on submarines or ships or at shore stations for detection and for determination of the bearing and the range of ships and other marine craft.
6. To guide heat-homing missiles.

Both the U. S. Army and Navy requested NDRC to set up projects with these developments as the goal. Under the auspices of Section 16.4, such projects were initiated at Western Electric Company (BTL) under Contract OEMsr–636, at Harvard University under Contract OEMsr–60, and at the University of Michigan under Contract NDCrc–185. Infrared receiving systems were developed under each contract for one or more of the purposes listed above and final reports on these developments have been submitted to NDRC. This chapter concerns itself with the discussion of the complete receiving units which, in all cases but one, employ detectors such as are described in Chapter 8 of this volume.

The various devices which have been developed under the auspices of Section 16.4, NDRC, are summarized in the following paragraphs.

The *portable infrared detector* [PND] was a development of BTL Contract OEMsr–636 for the use of military field personnel primarily to detect personnel, vehicles, tanks, small boats, and ships. The instrument is a lightweight, self-contained, hand-pointed device which employs a two-strip thermistor bolometer situated at the focus of a parabolic mirror. A small vibrating mirror sweeps the target image back and forth from one bolometer strip to the other. The instrument has an instantaneous field of view about 70x10 minutes, and may be turned at about 2 degrees per second while searching for targets. The electrical system consists of a 20-c signal amplifier and an 800-c bridge. The 20-c signal modulates the 800-c tone to give an aural signal in headphones or loudspeaker. Visual signals may also be had with a separate indicating unit. Section 9.4 contains a description of the PND and data on its performance.

The *scanning infrared detector* [SND] was developed by BTL under Contract OEMsr–636 for the purpose of locating moving tanks. It was designed to detect small temperature differences within a sector of 30 degrees scanned at the rate of 30 to 60 degrees per second. A two-strip thermistor bolometer is mounted at the focus of a scanning parabolic mirror, and the instantaneous field of view is from 0.5 to 4.0 degrees by 0.08 to 0.16 degree, depending on the bolometer design used. The electrical system amplifies the signal

[a] Department of Physics, University of Tennessee, Knoxville, Tennessee.
[b] Mendenhall Laboratory of Physics, Ohio State University, Columbus, Ohio.

from the bolometer and presents it on waxed recording paper. Each signal causes a stylus to mark the paper, which advances a small distance for each scan. The target thus leaves a trail of marks on the record paper. A description of this equipment and results of the field tests are given in Section 9.5.

The *thermal map recorder for ground survey* [TMR] is an airborne infrared receiver and recorder developed by BTL under Contract OEMsr–636. It was designed primarily to permit night scanning and mapping of regions to determine if they contain suitable military targets for heat-homing bombs. The device, placed in the nose of a bomber-type aircraft, will plot a strip map of temperature differentials or discontinuities found on the earth over which the plane flies. It can be adjusted to provide a map with dimensions of equal length and breadth or one in which the length is some chosen factor of breadth. The forming of the map may be observed in flight. A description of the equipment and an account of some of the flight tests are given in Section 9.6.

The *thermal receiver with remote indicator* (Type L), developed by BTL under Contract OEMsr–636, is a device for use in an airborne weapon. This weapon consists of a mother aircraft and a drone to be used for the destruction of enemy naval surface craft at night. By radar, primary search and location of the target are assumed to be accomplished by the control aircraft preliminary to the release of the drone. After the drone is released it is controlled by radio. From its scanning device it derives positional information and data as to what course should be followed to cause a collision and the proper time for diving. This is presented on a suitable screen to the operator of the mother aircraft. Section 9.7 contains a description of this equipment and records of typical performances in the field.

The *far infrared bombsight with angular rate release* [FIRBARR] is a device designed to scan and establish a line of sight to any heat target by using the infrared radiation from the target. The preliminary investigation of the practical possibilities of such equipment, carried out by BTL under Contract OEMsr–636, is discussed briefly in Section 9.8.

The *portable ship detector* [PSD], which was the first of the receiving systems to be developed, is a small, manually pointed, scanning receiver for the detection and determination of the bearing of ships. It was developed by Harvard University under Contract OEMsr–60. The signals are detected by a thermistor bolometer mounted in the focal plane of a Schmidt optical system. After amplifying, they are presented as either an audible or a visible signal. This equipment is described and information on its performance is given in Section 9.9.

The *stabilized ship detector* [SSD] was developed by Harvard University under Contract OEMsr–60 when it became clear that search was too difficult with the PSD mounted on the deck of a ship. It is a synchro-driven device utilizing thermistor bolometers in the focal plane of a Schmidt optical system. With this equipment it is possible to obtain good bearing accuracy and target resolution. A permanent record is made of the true bearings of all targets which are detected within the angle scanned. The SSD is described in Section 9.10 and representative records of its performance are given.

An *intermediate infrared receiver* [IIRR] was designed, assembled, and tested by the University of Michigan under Contract NDCrc–185 to investigate the practical usefulness of such equipment for the detection of military targets. It comprised an exploratory model of an intermediate infrared receiving equipment utilizing a lead sulfide photoconductive detector cell. Its design and performance are discussed in Section 9.11.

The *far infrared rangefinder* employing wavelengths in the 8- to 14-μ spectral region was developed by Harvard University under Contract OEMsr–60. The equipment operates on the principle of the standard optical rangefinder, except that the "eyes" are metal-strip bolometers. With this device, ship ranges to 10 per cent or less, and bearings to ±1 minute of arc or less may be determined at night or in haze. It is effective to at least 5,000 yards. Automatic horizontal guiding was developed to make the apparatus useful on an invisible target. A description of the device and data on its performance may be found in Section 9.12.

9.1.2 Aspects Common to All Systems

All the foregoing pieces of apparatus have certain characteristics in common; for example, they are all equipped with more or less equivalent optical

systems, detectors, and amplifiers; they are sensitive to the same general interval of wavelengths in the spectrum; their efficacy of operation is essentially related to the thermal contrast between the target on which they are trained and the surrounding background, etc. The following sections review briefly some of the aspects which the devices have in common and which are important in determining the excellence of their performance.

Optical Systems, Detectors, and Amplifiers

Each of the devices considered in this chapter is equipped with a light-gathering system which in turn concentrates the radiant energy on the detecting element. In the PND, the SND, the TMR, the Type L, the IIRR, and the infrared rangefinder, the light-gathering unit is a parabolic mirror, while in the PSD and the SSD a Schmidt assembly is used. In all cases the detecting element is located at the focus of the optical system.

The choice of the optical system which is most suitable to a certain detection problem depends upon the "field of view" involved in the detection scheme. By field of view is meant the solid angle which is "seen" by the detector at a given instant during the scanning motion. Land-based equipment for scanning a sea horizon should have a very small vertical field in order to minimize noise and false signals originating in the background. On the other hand, homing devices require quite large fields of view.

If a small field is satisfactory, the rays entering the optical system will be very nearly axial, and sufficiently good images will probably be formed by using a parabolic mirror to gather the light. If the field is large, however, the images which are formed off axis are important and a parabolic mirror may not be satisfactory. A spherical mirror with a refracting plate placed at its center of curvature to correct for spherical aberration forms what is known as a Schmidt system. Images formed by such a system are found to deteriorate slowly as the images go off axis. For fields up to 1 degree parabolic reflectors give sufficiently good images for most purposes.

Except for the IIRR and the infrared rangefinder, the detecting element is a thermistor bolometer developed by the BTL under Contract OEMsr-636. In the IIRR a lead sulfide cell developed at Northwestern University under Contract OEMsr-235 is employed, while the infrared rangefinder uses a nickel-strip bolometer of a squirrel-cage design. Every one of these devices has some method for vibrating the image of the target on and off the detector so that the signal produces a heating and a cooling of the bolometer, thereby effecting a pulsating current which facilitates amplification for recording or observation. Although the details of the amplifiers vary considerably from case to case, they have the same two essential parts, a preamplifier and a main amplifier. In all cases, except the IIRR, the detecting elements were made a part of a bridge arrangement which was included as a part of the preamplifier unit. In general, the main amplifier has been designed to have a narrow band-pass to reduce the inherent noise of the system.

The current which flows through the bolometer is considered an average of the electron flow. Statistical departures from this average occur and with them occur fluctuations in the voltage across the bolometer, known as Johnson noise. This form of thermal agitation noise sets the lower limit on the signal which can be detected. The Johnson noise measured across a resistor will depend upon the temperature of the resistor, the magnitude of the resistance and the width of the frequency band in which the noise is measured. It is for this reason that the main amplifier is designed with narrow band-pass widths.

The Importance of Atmospheric Attenuation

The atmosphere contains certain amounts of water vapor, carbon dioxide and other compounds of organic nature. These vapors all have characteristic absorption spectra. Because of the absorption bands of molecules in the air, the atmosphere is virtually opaque to infrared radiation at wavelengths greater than 2.5 μ except in a few "window" regions. Because objects of military interest have virtually all of their "incandescence" at wavelengths greater than 3 μ, only two of these windows are of interest, those from 3.0 to 4.0 μ and from 8.0 to 14.0 μ. With the exception of the IIRR, all the devices described in Chapter 9 depend principally upon the radiant energy in the 8- to 14-μ window for their operation. The IIRR operates on the radiation transmitted by the 3.0- to 4.0-μ window. The attenuation of infrared radiation by the atmosphere is discussed in more detail in Section 9.2.

THE IMPORTANCE OF CONTRAST BETWEEN TARGET AND BACKGROUND

All of the receivers discussed in this chapter depend for their operation upon comparing the radiation received from a target with the radiation received from an equivalent amount of background. This comparison is affected by oscillating the target image off and on the detector strips. It is evident, therefore, that the contrast between the target and the background is of prime importance in the detection of objects at a distance by their self-emitted radiations.

Drifting clouds along the horizon and light reflected from the surface of the sea send out signals which tend to obscure a target. Variations in the background signals due to various meteorological or other causes are frequently referred to as *background noise* if they are erratic or *background signal* if they are steady. (For further discussion, see Section 9.3.3.)

9.2 ATMOSPHERIC ATTENUATION OF INFRARED RADIATION

9.2.1 Introduction

The transmission characteristics of the atmosphere are of primary importance in determining the maximum range within which devices for signaling, for communicating, and for detecting objects of military interest can be successfully operated if they use self-emitted infrared radiation. It is, moreover, important to know how infrared radiation is transmitted by smokes of various kinds in order to determine how effective a smoke screen might be against the detection of objects of military importance.

The information previously available on the transmission of infrared radiation by the atmosphere was only fragmentary, and the transmission through smokes was virtually unknown. To obtain more complete information on this subject for the Armed Forces, a project was requested in joint Army-Navy Project Control AN-32 and begun at Harvard University.

It was shown that attenuation by water vapor, from the visible to 2.7 μ, was due mainly to a deepening and widening of the water vapor bands, but that the attenuation between these bands was very weak. The measurements were carried out in conditions of high summer humidity and for very long optical paths, using the sun as a source. Measurements under varying degrees of haze were also made. The attenuation by the water vapor in a path length of 5,000 yards was small in the 8- to 14-μ region. Probably more important were the measurements made on this window region using the sun as a source just after it had risen from the sea. The transmission properties of several types of smokes were measured.

9.2.2 A Résumé of Earlier Work

The attenuation of infrared radiation in the atmosphere is produced by the absorption of carbon dioxide and water vapor and by the scattering of fog, clouds, smoke, etc. For this reason only the wavelength between these absorption bands can be used for infrared transmission and the only important usable window is the previously mentioned 8- to 14-μ spectral region.

THE 8- TO 14-μ WINDOW

The 8- to 14-μ window is bounded on the short wavelength side by the great water vapor vibration-rotation band centered at 6.2 μ and on the long side by the carbon dioxide bands centered at 13.9, 15.0, and 16.2 μ and also by the pure rotation spectrum of water vapor. There is an absorption band in the window at 9.5 μ due to ozone in the upper atmosphere, but this is of no importance for absorption paths along the earth's surface.

Radiation Absorption by Water Vapor. The 8- to 14-μ window is not perfectly transparent. The amount of attenuation is determined by the amount of water vapor in the path, even though no water vapor band is centered in this region.[1] The absorption lines in a spectrum have a finite width and a shape resembling a resonance curve. With a very small amount of absorption, only the central peaks of the absorption lines are important; with a large amount, the wings of the absorption lines are also important and may produce a considerable absorption far away from the line center. In the 8- to 14-μ region there are no water vapor lines of any consequence, so that any water vapor absorption in this region must come from the wings of absorption lines lying at higher and lower wavelengths. The overlapping of the wings of the many lines of the 6.26-μ vibration-rotation band on one side of the window

and the rotation lines on the other side serve to give a nearly constant absorption coefficient throughout the window region. Because of this lack of line structure in the window region, the absorption follows Lambert's law to a good approximation.

If the transmission in the window region is less than 50 per cent, then Lambert's law ceases to be a valid approximation and a more complicated expression must be used.[1] A series expansion of this complicated expression is

$$\frac{\Delta E}{E} = 0.45(0.53l) - \frac{(0.53l)^2}{4}$$

where $\Delta E/E$ is the fraction of absorbed radiation and the numerical constants have been chosen to fit experimental data. In this formula l is a measure of the amount of water vapor in centimeters of precipitable water. If all of the water vapor in a column 1 square centimeter in cross section along the absorbing path were condensed into a cylinder of water of equal cross-sectional area, then the length of the water cylinder in centimeters is the number of centimeters of precipitable water.[2,3,4]

Radiation Absorption by Organic Vapors. In addition to the absorption in the window region by water vapor there may be absorption by organic vapor also.

It is known that many complicated organic molecules absorb heat radiations strongly and if the vapors which give the sea its characteristic odor, or associated organic vapors, also absorb strongly in the 8- to 14-μ region, one might expect excessive attenuation in summer. These vapors are given off to the surface air more copiously by the warmer water, and they remain near the surface because the surface air is then more stable due to the even higher upper air temperatures.

Radiation Scattering by Fogs. The transmission of far infrared radiation through fog has been found to be as poor as for visible radiation.[1] This seems strange when one considers the penetration of haze by near infrared radiation. A consideration of the particle size, however, will explain the situation. Scattering by particles becomes important when the particle diameter is equal to, or larger than, the wavelength of the radiation under consideration. Haze particles are very small, being about 1 μ in diameter. Such particles attenuate visible light but allow the near infrared radiation to be transmitted. Fog particles are about 20 μ or larger in diameter and therefore are opaque to 10-μ radiation in the window region.

9.2.3 Recent Measurements on Atmospheric Attenuation of Infrared Radiation [5]

The attenuation of infrared radiation of various wavelengths from the visible to 2.7 μ and throughout the 8- to 13-μ window has been investigated with a recording prism spectrograph.

The Radiation Sources

As a source for the radiation of wavelengths less than 2.7 μ, a tungsten filament lamp was used, and for greater wavelengths a heater was used as a source. The sources were mounted on a hill 50 feet above the sea at the focus of a 5-foot reflector at Fort Ruckman. The receiving equipment, including the spectrometer, was set up 5,000 yards away, across Broad Sound, at Fort Heath. In many of the experiments the sun was used as a source, the energy being concentrated on the spectrograph slit with the aid of a heliostat. The optical path in this case was determined by the zenith angle of the sun and was a maximum when the sun had just risen out of the sea.

The Spectrometer

The radiation was gathered by a collimating mirror and dispersed by a prism. For wavelengths less than 2.7 μ a glass prism was used, and for longer ones, a prism of rock salt. The dispersed radiation was gathered by a telescope mirror which forms a spectrum at its focus.

The telescope mirror and prism are rotated together, causing the spectrum to sweep across the bolometer strips, which serve also in the capacity of an exit slit. A photograph of the spectrometer and telescope is shown in Figure 1.

The Detecting and Recording System

As a detector a bolometer was used made of two collinear strips ⅛ μ thick and about ½ millimeter wide. The strips were about 6 millimeters long and were mounted in a cell with a NaCl window filled with hydrogen to a pressure of 5 mm of Hg. The strips were coated with aluminum black. A rotating disk was used in the collimating system to chop the incident radiation at a frequency of 10 c.

The bolometer was connected electrically to a

twin-T amplifier of about 0.5 c pass-band width. The a-c voltage of this amplifier is rectified by an electronic component which functions in such a manner that its d-c output voltage is very nearly pro-

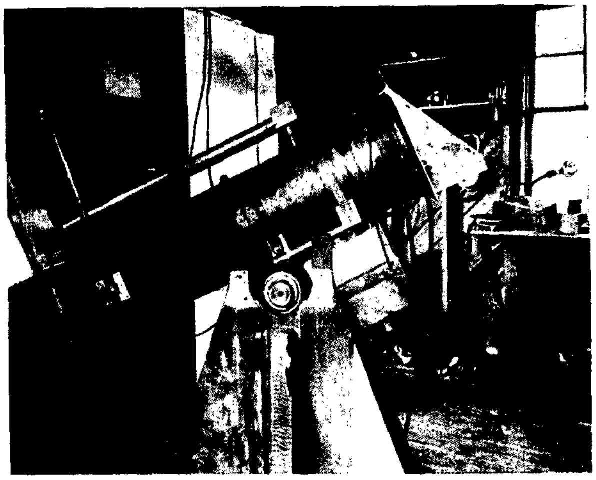


FIGURE 1. Telescope and spectrometer for measurements of atmospheric attenuation of infrared radiation.

portional to the logarithm of its a-c input voltage. This logarithmic output is fed to an Esterline-Angus recording milliammeter which records the action of the bolometer, or the bologram. Wavelength positions on the bolograms are determined by interpolation from the characteristic atmospheric bands. A typical bologram is shown in Figure 2.

Method for Determining the Attenuation

In determining the attenuation by a column of gas it has been standard practice among infrared spectroscopists to compare the energy transmitted through the gas path with that transmitted through an equivalent evacuated column. Such a procedure is, of course, impracticable here, since this would require an evacuated cell of 5,000 yards. An alternative method is used and depends upon the following procedure. It is observed that the radiation at wavelength 2.16 μ is independent of the amount of water vapor in the optical path and is, moreover, independent of the haze condition. This may be taken to mean that radiation of this wavelength comes through the atmosphere unattenuated under virtually all conditions. If now the form of the radiation curve of the source were known (it is probably not a black body) an envelope of the initial radiation could be determined using as a scale point the magnitude of the energy transmitted through the atmosphere at wavelength 2.16 μ. The actual form of the radiation curve of the source is obtained by making a set of measurements on the

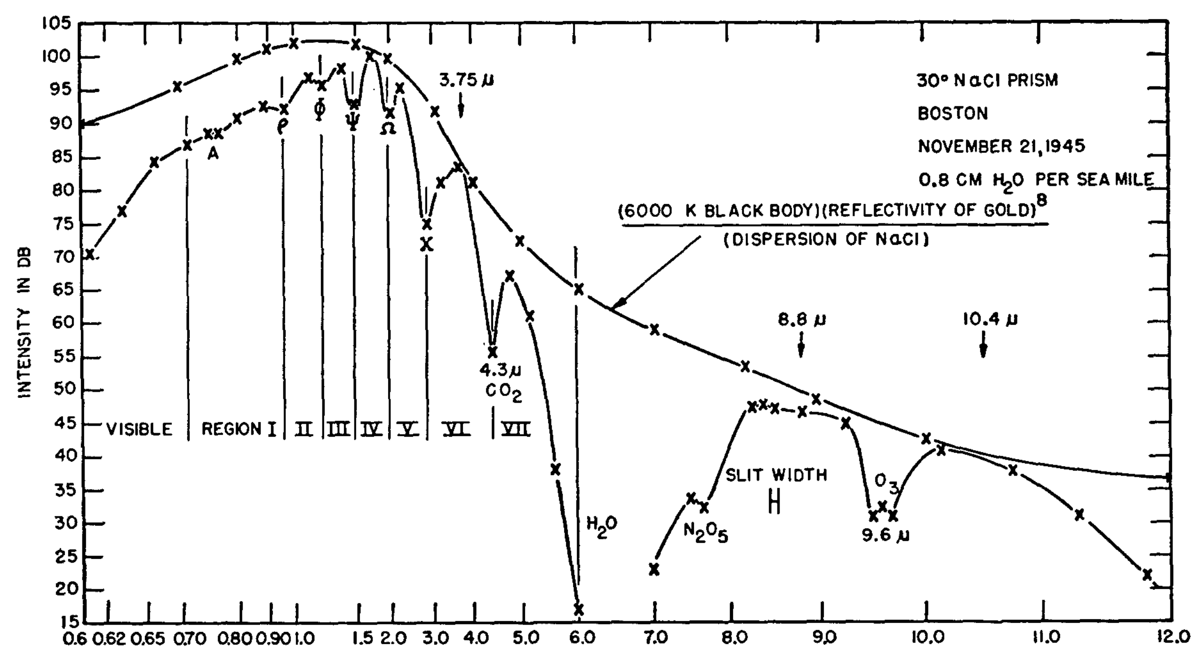


FIGURE 2. Solar bologram showing atmospheric bands.

source at a distance of 14 yards, at which distance the attenuation on a dry day may be regarded as negligible. Such an envelope calculated for the incident radiation occurs as a continuous line above the attenuated curve in Figure 2.

When the logarithmic response curves are converted to arithmetic the ratio of the areas under the attenuated response curves to the corresponding areas under the envelope curve serves as a measure of the radiation transmitted.

While the 2.16-μ region remains unattenuated also by haze this is not the case with the region near 0.86 μ. This fact can be made to define the amount of haze present in terms of the difference between the intensity at 0.68 μ, expressed in decibels, minus the intensity at 2.16 μ.

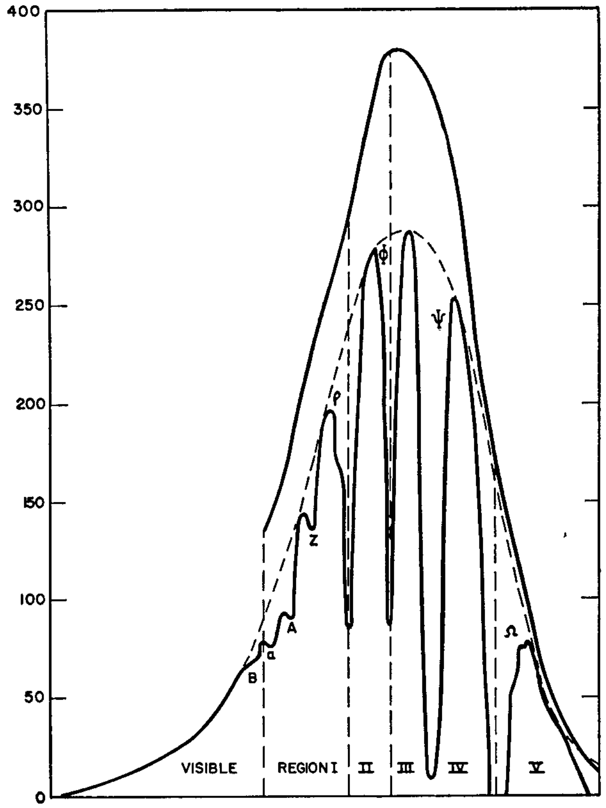


FIGURE 3. Solar bologram showing atmospheric bands.

The bologram shown in Figure 3 has been converted from a logarithmic to an arithmetic response curve. In Table 1 are given the ratios, under varying degrees of humidity and varying degrees of haze, of the areas of the attenuated response curves to the computed arithmetic response envelope curves which serve as a measure of the transmitted radiation. Bands I to V referred to in Table 1 are, respectively, at 0.70 to 0.92 μ, 0.92 to 1.1 μ, 1.1 to 1.4 μ, 1.4 to 1.9 μ, and 1.9 to 2.7 μ.

TABLE 1. Ratios of areas under arithmetic curves to area under envelope.

Spectrogram	Water (cm)	Haze (db)	I	II	III	IV	V
1	1.1	1.3	0.91	0.90	0.79	0.68	0.57
2	3.5	0.4	0.82	0.83	0.67	0.61	0.55
3	7.5	0.0	0.75	0.75	0.59	0.59	0.54
4	7.3	20.0	0.79	0.73	0.58	0.47	0.54

Figure 2 shows a solar bologram which indicates the transmitted spectral intensities to wavelengths of 12 μ. The interval from the region marked χ to the 4.3-μ CO_2 band (Region VI) is of especial interest, since it marks a window in the near infrared. The region from 4.3 μ to the great water vapor band (Region VII) delineates another window of less importance. The transmission by the atmosphere for wavelengths longer than 3 μ may be obtained approximately with the aid of the curve in Figure 2 and the envelope which is constructed for a black body (the sun) at 6000 degrees K.

The transmission between the regions marked Ω and χ is known to be high from earlier measurements. The apparent low transmission indicated for this region in Figure 2 is from falsification due to the slit width. This occurs when the slit is so wide that it subtends a sufficiently large wavelength interval so that the bolometer reading between Ω and χ is influenced by the absorption in these regions. In other words the absorption bands, and the window between, are not fully resolved.

Similarly, unresolved ozone and water vapor bands account for the apparent low transmission in Regions I and II.

Discussion of Results for Ship-Fired Smokes

The final results for all ship-fired smokes are given in Table 2.

These densities are all adequate to be completely opaque visually for the 1,000-watt searchlight.

The FM, FS, and fog-oil smokes are less opaque, according to results obtained, than HC smokes, and by a factor of about 4. HC, FM, and FS have comparable loss of opacity with increasing wavelength throughout the visible and near infrared. FS is rela-

tively more opaque in the far infrared than FM, but even so it is far from being an effective screen there; a plume opaque to our 1,000-watt searchlight attenuates only 4 db at 9 μ.

TABLE 2. Results for ship-fired smokes with relative ship-air velocity at 10 knots.

	HC smoke	
(1 pot = 32 lb of smoke or 32/6 lb per minute of smoke)		
$\lambda = 0.85\ \mu$	Attenuation per pot	20 db
2.10 μ		4 db
9.0 μ		1 db
	FM smoke	
$\lambda = 0.85\ \mu$	Attenuation for 30 lb FM/min	18 db
2.10 μ		9 db
9.0 μ		3 db
	FS smoke	
$\lambda = 0.85\ \mu$	Attenuation for 30 lb FS/min	15 db
2.10 μ		4 db
9.0 μ		4 db
	Fog oil	
$\lambda = 0.85\ \mu$	Attenuation for 30 lb FO/min	15 db
2.10 μ	For a "parallel run"	16 db
9.10 μ	For a "parallel run"	2 db

Fog oil increases its transmission most rapidly with wavelength and at 2.2 or 9 μ its attenuation is ordinarily negligible. In order to get any measurable attenuation at these wavelengths, the smoke-generating ship was run almost parallel with the wind, quartering only enough to keep out of its own smoke. This produces a very dense plume of smoke. The generator put its maximum output in this plume for about 5 minutes. These fog-oil runs are referred to in Table 2 by the designation "parallel run."

The general conclusion that one comes to is that none of the smokes are effective for the far infrared, or even for the intermediate infrared at approximately 2 μ.

A study of smoke transmission has been made at the U. S. Naval Research Laboratory [NRL] and is covered by Report H-1602 of March 25, 1940. The results for HC smoke obtained at NRL and stated in this report agree generally with those obtained by the Harvard project.

TEST OF GASEOUS SCREENS FOR $\lambda = 9\ \mu$

Field tests were carried out to determine if appropriate gases with absorption bands in the region 8 to 14 μ would afford effective screens. The three gases SO_2, C_2H_4, and C_2H_6 have strong absorption bands which together cover this spectral region. They were liberated from shipboard together with FM. The FM smoke was used as a marker to give evidence that the gases actually crossed the optical beam.

Also NH_3 was liberated, in a second run, together with FM as a marker, to determine its efficacy as a far infrared screening gas.

The regular 5-degree NaCl dispersing prism was used with the bolometer set at the maximum response, as previously used with the smoke screens.

A combination of C_2H_4, C_2H_6, and SO_2, liberated respectively at rates of 9, 9, and 4 pounds per minute, with FM marker, gave an immeasurably small attenuation although it was known that the gases actually crossed the optical beam. The result was similarly negative with NH_3. The exact weight of the NH_3 cylinder could not be determined, since its weight (400 pounds gross weight) exceeded the capacity of the available scales. Its valve was opened wide for the run and a substantial amount of gas was discharged and crossed the optical path.

9.3 THERMAL RADIATIONS FROM TARGETS AND BACKGROUNDS

9.3.1 Introduction

All natural and military objects may be said to be "incandescent" in the wavelength region from 8 to 14 μ. Because there is very little atmospheric attenuation of wavelengths from 8 to 14 μ, radiation in the wavelength interval has been used for the detection of objects of military importance, for signaling purposes, and for guiding homing devices. The infrared detectors are, in general, made to compare the radiation received from a target with that from an equivalent area of the background, and their operation depends upon the differential in the emission from the two.

If the background is uniform and unchanging the contrast between it and the target may be large and detection will be a simple matter. Usually, however, the background is not uniform, particularly over the sea. At the horizon will be found floating clouds which may be at temperatures different from the sky. As they float by they emit signals. The waves themselves may reflect light to the detector which is interpreted as a signal. The water, which in general is at a temperature different from the target, may illuminate the target with radiation characteristic of its temperature. This

footlighting may be seen by the detector and produce a false signal.

The background effects which have been named send out signals or noises which are detected by the receiver. Their net effect is to destroy the contrast between the background and the target, particularly when the target is distant. For the purpose of determining the ease with which military targets can be detected at various ranges by means of low temperature radiations, a survey of targets was undertaken at Harvard University under Project Controls AC–225.02, NO–183, and NS–163 (revised).

9.3.2 Emission of Targets and Backgrounds[2]

The detectability of a target is determined by consideration of its overall black-body temperature (or by the distribution of temperature over the surface of the target) together with the black-body temperature of the target background. The temperature thus specified is the temperature of a black body which would have an emission equivalent to that of the target or background.

Emissions and corresponding black-body temperatures have been determined for the various parts of a ship surface (and for backgrounds) by means of a simple measuring device comprised of a thermopile at the focus of a mirror together with auxiliary electrical measuring equipment. Two auxiliary black bodies at known temperatures were used for calibrations.

Measurements of target temperatures were made with this equipment as follows: the thermopile was focused successively on the ship's surface and on the two auxiliary black bodies. The latter were controlled so that their emission bracketed the ship's emission. Three readings were obtained, corresponding to the emission of the ship's surface and the emission of the two black bodies. The equivalent black-body temperature of the ship's surface was derived from these readings and the two known temperatures by linear interpolation. In order to cancel the effect of an air-path absorption, the auxiliary black bodies were placed, wherever possible, at approximately the same distance as the tested surface. Some observations were taken with the measuring equipment near the ship's measured surface and some were taken from a station entirely separate and remote. In the latter case, the distances, respectively, of the target and of the auxiliary black bodies from the measuring apparatus were not equivalent.

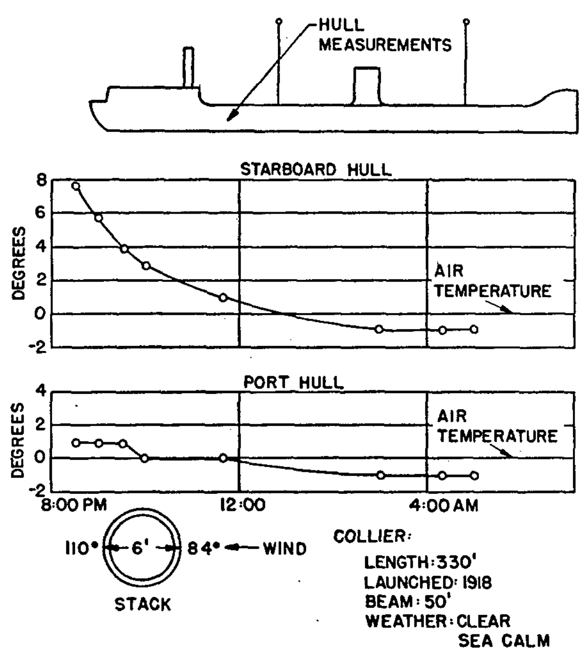


FIGURE 4. Diagram showing measurements on temperatures of a target.

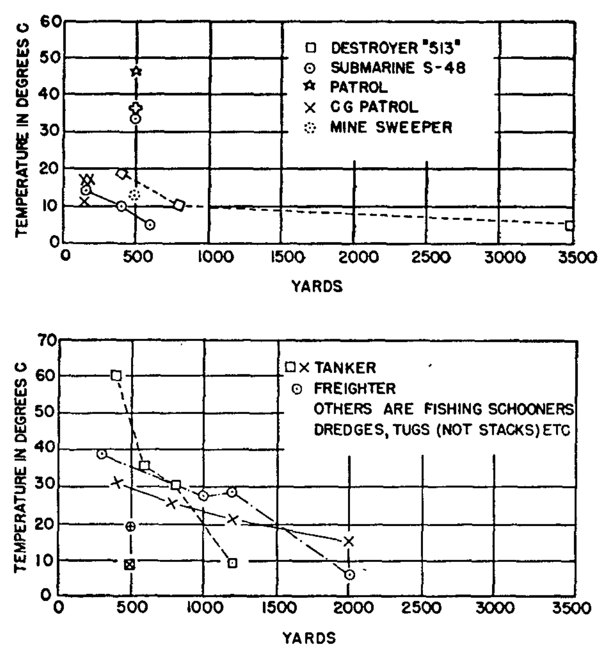


FIGURE 5. Graphs of observed differential temperatures (ship minus background) against ranges.

Figure 4 is an example of the results obtained on board or near ships in Boston Harbor and on board

ships at sea. Stack temperatures ranged near 100 C, except an insulated stack which was about 20 C. A considerable variation in measured temperature, as determined from various viewing angles, is produced by reflected sunlight and winds.

The observed differential temperatures (ship minus background) are plotted in Figure 5 for various ships as functions of their ranges.

9.3.3 Background Noise and Background Signals

The detection of ships by means of their infrared radiation depends on their thermal contrast against the background. When ships are at great ranges their emission may be confused with variations and fluctuations of the background radiation. Fortunately, as compared to land backgrounds, the sea provides a very uniform one.

The word "variation" is taken to mean the variation of the apparent temperature of background from point to point at any given time. The word "fluctuation" is taken to mean change of the apparent temperature of the background with time at any given point. Variation might be produced by reflection in the sea of the radiation of the clear sky and fluctuations might be produced by reflection in the sea at one point of drifting clouds.

The variations and fluctuations of backgrounds may produce spurious response in receiving instruments. This spurious response is called *background noise* if it is erratic and *background signal* if it is steady.

Origins of Background Noise and Background Signal

Variations and fluctuations of the temperature immediately in front of an infrared detector may also give spurious signals and noise. The air, where it is transparent, does not emit infrared radiations, but it emits on either side of the 8- to 14-μ window, where it is not transparent. Accordingly, inhomogeneities of the temperature of air, near receivers, can produce spurious response.

Such inhomogeneities have been found to produce fading in the signals obtained with the Type L detector.[6] Large signals faded to nothing within a ⅓-second interval. The fading occurred in gusty, moist atmosphere but not in either alone.

The study of background noise and signals is not a subject which can easily be treated in general, since the response, produced by variations and fluctuations of the background, of any particular receiving equipment depends intimately on the field of view of the equipment and the method of scanning which it employs.

Background variations and fluctuations can be most appropriately determined with the receiver which is to be used in practice or with a receiver which simulates the field of view and method of scanning to be employed. However, if fluctuations and variations are determined with a receiver which has a smaller field and a faster time constant than the field and time constant which characterize the receiver to be used in the field, then the fluctuations and variations which should be obtained with the field equipment can be predicted by integration. If, however, the field of view of the background measuring instrument is larger and if its time constant is slower, the results will not permit a complete prediction of the behavior of the actual receiver to be used in the field.

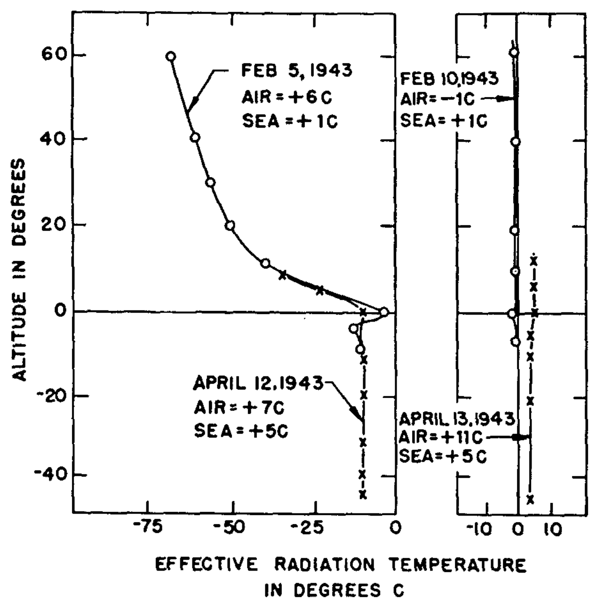


Figure 6. Vertical variation of apparent sea and sky temperatures.

Variations and Fluctuations of Background

The ease with which a ship or target is detected at sea depends, in addition to the amount of radiation it emits, upon the radiation reflected from it. Consequently, a target is more readily distinguished

under certain conditions of radiation than under others. These conditions will, of course, also affect the light reflected by the sky itself.

Figure 6 shows the vertical variation of apparent sea and sky temperatures with clear and overcast sky conditions. These measurements were made from Castle Island in Boston Harbor and from a tall building in New York. They show the role which the reflected sky light plays to produce a vertical variation of apparent sea temperature near the horizon. From Figure 6 it is evident that a complete overcast greatly decreases this vertical variation of background temperature.

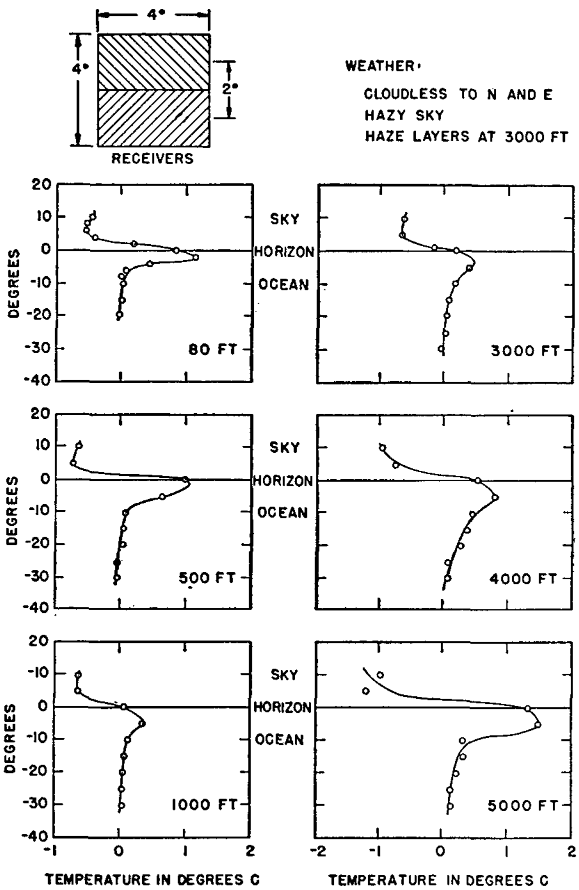


FIGURE 7. Background derivatives for Atlantic Ocean.

The vertical variation of the apparent temperature of the sea and sky background has been measured with a compensated receiver arranged so that it is sensitive only to the gradient of background temperature. The receiver is shown diagrammatically in Figure 7, together with results obtained with it at elevations from 80 to 5,000 feet. The observations at 80 feet were taken from a coast observing station. The other observations were taken from the air.

The contribution of reflected infrared radiation to produce fluctuations of the apparent sea temperature will depend on the reflectivity of sea water for the 8- to 14-μ radiations. Also, the contribution will depend on the character of the sea surface. This latter is locally dependent on wind and generally dependent on wave motion.

The qualitative application of the measured infrared reflectivity to predict the effect of various sky conditions in producing variations and fluctuations of apparent sea temperatures is facilitated by the fact that this infrared reflectivity is very nearly the same as the reflectivity of water in the visible. With this fact in mind, one can employ the visible variation and fluctuation of the appearance of the sea to predict the effect of various sky and sea conditions in the infrared 8- to 14-μ band.

Hulbert[7] has recorded some of the characteristics of sea reflections. Particularly, he says,

> The light of the rim of the breezy sea, i.e., the sea from the horizon to 3 degrees below comes mainly from the region of the sky 25 degrees to 35 degrees above the horizon and hence the reflecting facets of the sea which are visible to the observer are tilted up on an average at about 15 degrees from the horizontal. . . . A dark band of clouds rising up over the horizon does not darken the sea appreciably until it reaches an altitude of 25 degrees.

9.3.4 Dependence of Target Emission on Meteorological Conditions

The quantitative target-background temperature differentials reported above have been determined mostly in winter. Qualitative field observations made throughout the year indicate that the targets are relatively stronger in winter than in summer. For example, ships which are barely detected at a 5,000-yard range in summer have been detected at three times this range in winter.

Although the water vapor content of a given optical path in Boston Harbor may vary by a factor of 7 or more from summer to winter, it is not expected that the transmission for the 8- to 14-μ band will vary enough to account for the summer-winter differences in range limits. It appears that other factors may be involved.

Two possible factors for explaining the winter-

summer differences in range limits are: first, higher contrast may obtain between targets and backgrounds in winter (the cause of this is described later); and second, higher attenuation due to higher concentrations of organic vapors characteristic of sea air may obtain in summer.

FOOTLIGHT EFFECT

The vertical surface of a ship on a flat sea is exposed to radiation transfer from the warmer water in winter throughout a solid angle approximating π steradians; whereas, the detector is not exposed to such transfer because it "sees" the water at grazing incidence. It is because the water illuminates the ship's surface and cannot be seen that this effect is called the footlight effect.

For example, sea and air temperatures for winter and summer off Yokohama [8] are:

	Summer	Winter
Sea	25 C	17 C
Air	25 C	3 C
Difference	0 C	14 C

In summer and winter the cooling by so-called nocturnal radiation there is about the same. Thus, in summer, a vertical ship surface initially at the air temperature is in radiative equilibrium with the sea and is neither heated to a higher temperature nor cooled to a lower temperature by it. Whereas, in winter, a vertical ship surface initially at the air temperature is heated by the radiation from the sea to a higher-than-air temperature. For still air and for a 14-degree sea-air differential this effect is calculated to heat the vertical surface about 2 degrees above air temperature (or 2 degrees above the temperature it would otherwise have). Moreover, the heating of crew's quarters in winter adds to making a ship a relatively warmer target then.

Considered together with the greater water vapor and possible greater organic vapor attenuation in summer, these effects all operate to make winter signals produced by ship targets (viewed along a horizontal optical path) relatively much stronger than summer signals. When these factors have been quantitatively evaluated, especially since the new measurements of transmission reported in Section 9.2 are available, the detectability of ships under all meteorological conditions should be predictable.

9.4 PORTABLE INFRARED DETECTOR

9.4.1 Introduction

The *portable infrared detector* [PND][9] was developed by BTL under Contract OEMsr-636 as Project Controls N-108 and CE-37 for use by military field personnel for the detection primarily of personnel, vehicles, tanks, small boats, and ships by means of the intrinsic difference in temperature between the object and its immediate background. This development was initiated following suggestions by officers of the Engineer Board, Bureau of Ships, and Bureau of Ordnance that a model of a portable far infrared receiver be constructed for the purpose of testing whether a man could be detected at night through the reception of thermal radiation from his body at ranges of 100 to 200 yards.

During the course of the development the scope of this project was enlarged from the original purpose by later requests from the Armed Services to include the investigation of the most advantageous utilization of thermistor bolometers for detection of infrared signals, the development of associated receiving equipment, including electronic circuits and optics, and the application of such equipment for Armed Services needs, particularly the detection of the types of military targets referred to above.

Due care was taken in this development to assure a lightweight, compact unit, but no attempt was made to design the equipment for extremes of operating conditions such as very high and very low ambient temperatures, total immersion in water, extremely rough handling, etc.

This development has also served as a basis for the construction of the following related types of equipment under Contract OEMsr-636: the scanning infrared detector (see Section 9.5), the thermal map recorder for ground survey (see Section 9.6), and the thermal receiver with remote indicator (see Section 9.7), as well as for the preliminary survey on the far infrared bombsight with angular rate release (see Section 9.8).

9.4.2 General Description

The PND consists of two units, as shown in Figure 8, and may be carried and operated by one man. The first unit, which weighs only about 10 pounds (exclusive of tripod), contains the optical

system, double-strip thermistor bolometer, amplifier, headphone signal indicator, and the batteries in a cylindrical case. This unit is a convenient device for the detection of persons or other warm targets by giving aural signals. The second unit, which also weighs about 10 pounds, contains an auxiliary amplifier, loudspeaker, and visual indicator for use in lieu of headphones.

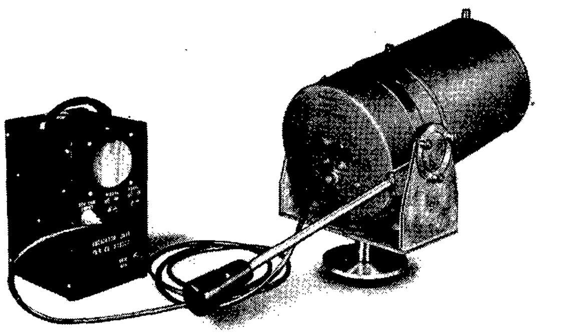


FIGURE 8. Photograph of portable infrared detector.

In operation the field of view is focused upon the parallel thermistor strips by means of an 8-inch parabolic mirror of 6-inch focal length and a small modulating plane mirror. The latter is vibrated so that it will focus the images of the target and of the adjacent background alternately upon each of the two bolometer strips 20 times a second in order to produce an a-c signal and to make the signal independent of any difference between the local temperature at the PND and the background temperature of the object viewed. The resulting a-c electrical signal from the bolometer strips is amplified by a 20-cycle amplifier and made to unbalance an 800-cycle bridge. The unbalance signal from this bridge may be heard with headphones or further amplified in the second unit for the operation of an indicator light or loudspeaker.

The field of view of the bolometer is 70 minutes in one direction and 6 to 10 minutes in the other direction. The minimum detectable radiant power incident on the reflector is about 1×10^{-7} watt. With this system, accurate results can be obtained by manually scanning over a plane angle of 2 degrees per second. Informatory but less accurate results can be obtained at a rate of 20 degrees per second with the plane mirror stationary.

9.4.3 Description of Component Parts of the PND

OPTICAL SYSTEM

Reflectors. The optical system has been described in a previous paragraph.

Bolometer and Angle of View. The bolometer consists of two thermistor strips, each 3x0.2 millimeter in size and mounted parallel to each other, behind a protecting window of NaCl with a spacing of 0.6 millimeter center to center, on a backing of glass or quartz. The field of view would be, for perfect optics, 0.002 radian along the strip and 0.0013 radian across the strip with an angular separation of 0.004 radian between the strips. Because the optics are not perfect the effective widths of the fields of view for each strip are somewhat larger, the circle of confusion of the mirror being about 0.5 millimeter.

The vibrating mirror is in its extreme positions most of its time. When the mirror is at the one extreme, the projection of one of the thermal strips, *A*, will be at location 1 and the projection of the other strip, *B*, will be at location 2. When the mirror reaches the other extreme position, the projection of thermal strip *A* is shifted to location 2 and the projection of thermal strip *B* is shifted to location 3, locations 1, 2, and 3 being closely adjacent to each other in order. If the integrated radiation is the same from each of the positions 1, 2, and 3, then no signal will result. Any difference such as that due to the presence of an object in the projected image of the strip at either position 1, 2, or 3 will give a signal and the strongest signal will be obtained when the object is in position 2.

VIBRATING MECHANISM

The ideal vibrating motion for the mirror is a periodic square wave of fixed amplitude and fixed period. This motion was accomplished by means of an electromagnetically driven torsional oscillator consisting of a piano wire, 4x0.16 inch, loaded by a soft iron armature to give the desired natural frequency.

A steel bar fastened to the wire is limited in its motion by a pair of stops at each extremity, and the small mirror, which is mounted on this bar, is therefore also limited in its amplitude of motion.

The steel bar spends most of its time at the stops and is quickly switched between the stops so as to produce a nearly square wave of motion at 20 c.

Detecting Element and Amplifier

Detecting Element. The closely matched thermistor strips which constitute the detecting element have a resistance between 1.5 and 3 megohms. The electrical characteristics of this type of bolometer have been discussed in Section 8.7.

Amplifier. The amplifier and batteries are contained in the cylindrical case just behind the main parabolic mirror, and the first stage of the amplifier is centered within this cylinder and shielded by a Permalloy case. The total amplification is produced in three stages, the resistance-capacitance coupling being so proportioned as to yield a frequency characteristic selective with respect to 20 c. The maximum 20-c gain is somewhat greater than 85 db, with the gain falling off by 6 db at frequencies of approximately 10 and 50 c. A suitable gain control is provided.

Following the three-stage selective amplifier is a bridge configuration employing the plate impedance of one of the miniature tubes as one of the arms. An 800-c oscillator is employed to excite the bridge, which is brought to a balance when no signal falls on the detecting elements. When a heat source is encountered, the vibrating mirror shifts the image back and forth across the bolometer strips at the rate of 20 c as already described. The application of this signal unbalances the bridge with the result than an 800-c tone, modulated at 20 c, is heard in the listening device.

Overall sensitivity of the amplifier is such that thermal noise due to the approximately 2-megohm input resistance presented by the bolometer provides audible modulation of the 800-c tone. Detection of a signal input of somewhat less than 1 microvolt is readily possible with the headphones, the distinctive 20-c modulation due to a signal being distinguishable even when several decibels below the average thermal noise level.

The battery supply arrangement for the bolometer unit is such as to bring the common connection of the two strips to the amplifier to approximately zero d-c potential with respect to ground, a condition which aids in minimizing microphonic effects resulting from movement of this lead.

Auxiliary Indicator Unit

Where the wearing of headphones is undesirable, the auxiliary indicator unit provides a loud-speaker, together with the additional gain required to attain about the same threshold sensitivity (under ordinary noise conditions) as that obtainable with the phones. This unit is compact and relatively light (about 10 pounds) and provides, in addition, a visual indicator which is particularly useful in noisy locations.

For aural indications, a two-stage amplifier serves to energize a small permanent-magnet type dynamic speaker. The frequency characteristic of the amplifier is such as to discriminate against both 20 cycles and harmonics of 800 cycles. For visual indications, a rectifier is employed to actuate a sensitive relay according to the envelope of the modulated 800-c signal applied to the amplifier. The relay, in turn, closes the circuit of a type 313A gas tube which glows with an orange color. The tip of this tube is visible at the top of the unit. As with aural indications, visual detection of signals below the existing noise threshold is possible, the rhythmic flickering of the glow tube on a true signal being distinguishable from the random flickering occasioned by noise peaks.

9.4.4 Operation and Operational Limitations

Operation

When a region is surveyed, the apparatus accepts all the radiation from the region that is not absorbed by the atmosphere, lost on reflection, or absorbed by the NaCl window on the bolometer. This includes actual radiation coming from the region viewed due to its absolute temperature and emissivity plus any reflected or scattered radiation falling on the viewed region from other sources. The apparatus compares this total radiation from a given object with the total radiation from each side of the object. Whether or not a signal is obtained depends on the magnitude of this difference. The response of the apparatus is not a linear function of signal strength. The response increases at first rapidly with increase in radiation strength and then saturates. The gain provided when the gain adjustment is maximum is sufficient to bring out the resistance or Johnson noise, tube noise, etc. Most

regions when viewed will give a multitude of signals when the gain is wide open. Exceptions to this are a clear sky, open water, or other uniform backgrounds. On a bright day objects of all kinds give signals. On an overcast or rainy day and at night, contrasts due to reflected radiation are at a minimum. It therefore follows that proper operation under such varying conditions depends on proper adjustment of the gain to a point where signals are not so numerous as to defy interpretation.

In use one can orient the apparatus so that the long dimension of the strips is at any angle that will give additional advantage in detecting a particular object. For example, if the background consists of objects that have a large vertical dimension, such as tree trunks, then each one gives a signal when the strips are vertically oriented, and if one is looking for a man or house back in the trees, this is difficult. If, however, the apparatus is oriented so that the strips are horizontal, then the tree trunks give no signal, but the man or house will, unless completely obscured. With the length of the strips in the horizontal direction, the horizon will give a signal. For a single observer in a locale of low ambient noise, the earphones are probably the best. In places of high ambient noise level, the visual signal obtained by using the indicator unit is by far the best. The aural signal from the loudspeaker is useful only in low ambient noise when several observers are present.

The small angular field of view of the PND 3 is very useful in locating the bearing of signals accurately. On the other hand, this field of view makes it easy to miss a target and also hard to hold one when found if operating on a nonstable platform.

While the apparatus is designed to work with the vibrating mirror, it has been found that it can also be operated with the vibrating mirror turned off. In this case, a signal is obtained when the image of the target is made to cross the bolometer strips. The optimum rate of motion is determined by the nature of the signal voltage transient and the pass band of the amplifier. This rate turns out to be about 20 degrees per second, as compared with 2 degrees per second when the vibrating mirror is on. In this way one can get information much faster. This method is especially useful where two or more prominent targets are moving with respect to each other, and one wishes to keep track of their approximate relative positions. This scanning method has also been used with an experimental recorder attached to the apparatus. It is found that there is a time delay between crossing the target and the arrival of the signal of about 0.05 second. Without the recorder, accurate bearing cannot be obtained with this scanning method.

Operational Limitations

Ambient Temperature. The lowest ambient temperature at which the equipment will operate satisfactorily was determined by the lowest temperature at which the batteries would operate. Because of certain materials used in construction, the PND 3 should not have been subjected to temperatures above 120 F.

Weather. Because the system is not strictly watertight, long exposure to high humidity would probably be detrimental. The rock salt window has a protective coating that will take actual drops of water on it without harm; however, the continuous presence of a water film on it would probably be destructive. The presence of a film of water covering any of the optical surfaces absorbs most of the useful radiation and greatly cuts the sensitivity. Experience has, however, shown that with a bright outside finish the apparatus will rarely get below the dew point. The apparatus will even operate in light rain unless the rain is blowing directly into the opening. As to dirt or tarnish on the optical surfaces, it is surprising how bad this will appear to be without appreciably affecting operation. It is strongly recommended that no attempt be made to clean any of these surfaces. If they become covered with a film of water, it is best to allow these films to dry by placing the apparatus temporarily in a dry place. Because of the construction the apparatus will probably not function very well in a head-on wind or air blast of any great velocity.

Shock. As regards extreme shock, such as dropping the apparatus, the controlling limitation will be how much damage will be done to the precision of the parabolic reflector.

Viewing through Windows. Use of the apparatus from the inside looking through almost any type of window will not prove satisfactory, since windows of glass and almost all thick materials will absorb most of the useful radiation.

Hot Sources. Moreover, the bolometer is a sensitive instrument and it has not been made to measure very hot sources. The local temperatures that

will result from pointing it directly at the sun will permanently ruin the bolometer.

Background Compensation. The PND was aimed at both very cold and very hot backgrounds, and the output noise was compared with the noise obtained when the radiation opening was covered. The compensation was not perfect, but for reasonably cold or hot backgrounds the increase in noise was less than a factor of 2. The greater the difference between background and ambient temperature, the greater would be this additional noise.

9.4.5 Range and Sensitivity

The range and sensitivity would naturally depend upon the optical alignment of the system. The alignment procedure was simple, however, and, when once adjusted, only a severe shock would knock it out of adjustment.

MINIMUM SIGNAL

By centering the PND on a small black-body source and reducing the source temperature, it was found that a signal of 0.1 or 0.15 μw could just be detected aurally. This corresponded to a flux density of 400 to 600 μμw per square centimeter at the parabolic reflector.

RANGE

The maximum range of operation of the PND depends upon the size of the target, its contrast relative to its background, and the atmospheric conditions. For example, hot objects, such as power plants, hot chimneys, etc., which are characteristic of regions of high population density, can be detected through haze that completely obscures vision.

Field tests carried out in cooperation with the Army Engineer Board in December 1943 and in March 1944 at Fort Belvoir showed the following typical ranges for the detection of personnel at night under reasonably good weather conditions: a man's hand at 500 feet; a man at 1,000 to 2,000 feet; three men clearly resolved at a range of 1,500 feet, even though the end men subtended an angle of only three degrees, and two men in a rubber boat at ½ mile. In tests made by Engineer Board personnel during July 1944, in the jungle near Fort Pierce, Florida, a man was detected at a range of 50 yards while so well hidden in tropical foliage that he could not be seen visually or detected in photographs.

In tests carried out at Lakehurst in cooperation with the Bureau of Aeronautics, the PND, mounted in a blimp, despite severe acoustical noise and vibration, definitely detected a coastwise vessel at a range of three miles.

In March 1944, tests of the PND mounted in a B-26 aircraft were made at Floyd Bennett Field in cooperation with the Bureau of Ordnance. At 4 P.M. at an altitude of 10,000 feet, with light haze and smoke present and the ground partly covered with snow, no signals were obtained from the water, but distinct signals were obtained from a large generating station, clusters of houses, wide roadways, and ships in the East River. In a field test at Dam Neck, Virginia, carried out in cooperation with the same bureau, to determine the possible usefulness of the PND as an antiaircraft gun detector at night, the PND detected a TBF plane flying at an altitude of 2,000 feet at a range of about 4,000 yards.

In field tests at the Bureau of Ships Test Station, Cape Henlopen, Delaware, in February 1944, of the land-based PND under favorable atmospheric conditions, the minimum range of approach without detection of an LCI (bow or stern view) was about 8,000 yards and of an LCT (bow or stern) was about 7,000 yards. With more favorable ship aspects, the LCI was reliably detected up to a maximum range of 11,000 yards and the LCT to 8,500 yards.

More intense heat sources, such as power plants and larger ships, should be capable of detection at considerably greater ranges. For example, in the Cape Henlopen tests, carried out with the Bureau of Ships, a cargo vessel was reliably detected to a maximum range of 17,000 yards.

9.4.6 Present Status

As a result of the field tests carried out at various places and under greatly varying conditions, the Army Engineer Board has placed a commercial order for pilot production of Penrod, which was the Engineer Board model of the PND. One-half of the initial order is allocated to the Bureau of Ships.

9.5 SCANNING INFRARED DETECTOR [SND]

9.5.1 Introduction

The imperative need of the Army for a reliable airborne scanning and recording equipment primarily for the detection of tanks, and the relative security with which an infrared receiver may be

operated, led to preliminary tests with existing infrared receivers at Fort Belvoir in September 1944. The equipment used consisted of a Model 3 PND (see Section 9.4) with headphones, a Model 3 PND operating with a waxed-paper recorder, and a Type L scanner-detector system (see Section 9.7) with cathode-ray presentation.

The promising results of these preliminary tests, together with the prior observation that useful signals could be obtained with the PND unit with the modulating mirror at rest if the line of sight of the device were waved (at an optimum scanning rate of about 20 degrees per second) across a heat source, led to the development by BTL under Contract OEMsr-636 of the *scanning infrared detector* [SND] [10] as Project Controls CE-37 and AC-225.020. The development was to provide an airborne, scanning infrared receiver with a suitable form of recorder in order to permit tests of such equipment for the detection of tanks, ships, and such other military targets as deemed desirable by the Armed Services and the NDRC.

Field tests (as described in Section 9.5.4) of this equipment have been carried out at night with the SND land-based, for the detection of tanks, hillside embrasures, and ships; with the SND airborne for the detection of tanks at night and ships in daylight, and for the mapping of land and shore-line terrain both at night and in daylight.

9.5.2 General Description

The exploratory research model SND constructed and set up for operation, as shown in Figure 9, consists of four sections (exclusive of the standard surveyor's tripod to hold the scanner-recorder). The parts are interconnected by means of shielded cables and are identified as scanner head and recorder, weight 22 lb; amplifier and control box, weight 20 lb; power converter and cable box, weight 23 lb; and 24-v storage battery box, weight 24 lb.

To meet various field conditions the equipment was made flexible as to type of bolometer used, scanning speed, electric passband, etc.

In operation the field of view is focused upon the thermistor bolometer detector by means of a parabolic mirror. The optical system and detector continuously scan a sector 30 degrees wide at a rate of 30 to 60 degrees per second. The amplified bolometer output actuates an electromagnetically operated stylus which makes a dot or short dash on a wax-paper chart to record the azimuthal locations of the heat sources from which signals are received. The position of the recorder stylus is mechanically synchronized with the angular position of the scanning head. The wax-paper chart is advanced at the end of each scan so that a time record of the received signals is obtained. The record reproduced in Figure 11 shows, for example, the type of record obtained from two moving tanks.

FIGURE 9. Photograph of scanning infrared detector.

A set of seven plug-in units, having "center frequencies" in the range from 27 to 150 c, controls the frequency passband and permits the selection of the optimum passband for the type of scene scanned.

For the set of instrumental conditions which give maximum sensitivity, the electric passband is centered around 27 c, the bolometer has a time constant of 7 milliseconds, and the scanning speed is 30 degrees per second. With this arrangement the minimum detectable radiant power incident on the 7-inch diameter reflector is 8.1×10^{-8} watt.

9.5.3 Description of Component Parts of the SND

Optical System

In the SND the bolometer unit is mounted rigidly at the focus of a gold-surfaced, glass parabolic mirror. The mirror is 7 inches in diameter and has a focal length of 6 inches and a circle of confusion of 0.25 millimeter. The mirror size and focal length were chosen after consideration of the available bolometer flake sizes, target size, circle of confusion, scanning speed, etc. The field of view of the optical system may be varied from 0.5 to 4 degrees high and from 0.08 to 0.2 degree wide, depending upon the bolometer flake size in the various plug-in bolometer units. For *point sources* on average terrain the desirable field is about 1.0x0.08 degree. The optical assembly is mounted within a cylindrical aluminum case on top of which is mounted the preamplifier.

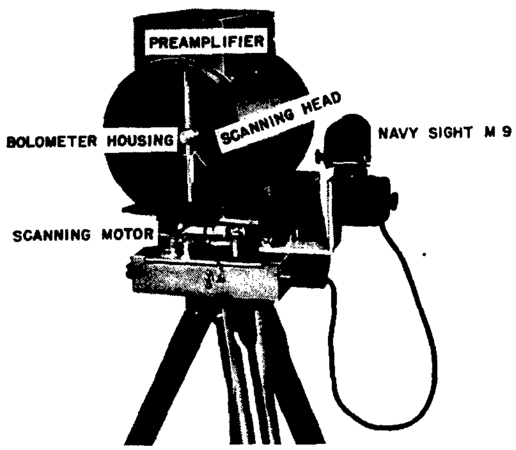


FIGURE 10. Photograph of scanning infrared detector (front view).

Figure 10 is a photograph showing the front of the scanning head assembly when mounted on a tripod. The principal elements of the assembly are titled in this photograph.

The mirror and bolometer housing takes the rather simple but sturdy form of 2 thick circular ribs bolted together to the interior of an aluminum alloy tube. Adjustment of the optics is accomplished by moving the mirror back and forth or tilting it with the adjustment screws.

Scanning Mechanism

Scanning is accomplished by oscillating the whole optical assembly with a motor-driven cam mechanism over a 30-degree sector at constant speed. Having mounted the optical parts and having provided an electric path to use the signal from the bolometer, it was then necessary to rotate the scanning head through an arc in a cyclic fashion in order to provide the heat transient which would upset the electric balance of the bolometer bridge. Mechanically, this scanning process could be performed most simply with a mechanism which provided a sine wave displacement function (in degrees). On the other hand, from the standpoint of the results desired, it would be preferable to have the scanning velocity, either right or left, a constant with time. The displacement function for this type of scanning if plotted versus time would then look like a sawtooth. When using the sine wave function for scanning, only perhaps 50 to 70 per cent of the total time would involve a scanning rate which was reasonably constant. On the other hand, the use of a sawtooth function for scanning would involve rather large accelerations at each turn-around point and all sensitive elements mounted on the scanning head would be subjected to the shock of vibrations set up at the turn-around point. The type of scanning function which has been decided upon in the SND is a compromise between the two types which have been described. The turning velocity of the head in degrees is reasonably linear over about 30 degrees but 2½ degrees are added for each turn-around point in the cam-drive design.

The scanning speed was from 30 degrees to 60 degrees per second, being dictated chiefly by the response time and size of available bolometers; the recording paper advanced $\frac{1}{25}$ inch at the end scan.

Detecting Element and Amplifiers

Detecting Element. Several different dispositions of paired bolometer flakes were used in a plug-in type assembly. For maximum sensitivity to small-sized sources on average terrain, two vertical strips, one above the other, were used. Each strip was from 1 to 5 millimeters high and 0.2 millimeter wide, the active areas overlapping slightly. In one of the dispositions the bolometers were obliquely mounted so as to permit an overlap in order that

there would be no dead spot at the center. The strips were aligned vertically so that an extended vertical source, such as a tree, would cross both strips at approximately the same time and give no signal through the bridge circuit. Small sources which cross only one strip would give a full strength signal. In another disposition the bolometer had only one active strip and gave a truer heat picture. Another possibility is to construct the bolometer with two active strips mounted side by side. A discussion of the characteristics of these bolometers may be found in Section 8.7.

In the case of the SND it was decided that the abrupt changes in the heat picture produced by boundaries and by small hot or cold sources would be the most important types of signals to record. The design was, therefore, based on the intention of making detection ability of the SND optimum for localized heat sources which were small enough to be considered point sources. On this basis, it turned out that the optimum results would be obtained when the bolometer time constant was approximately equal to the exposure time. With the SND scanning speed of 60 degrees per second, a 3-millisecond time constant was approximately right. The bolometer, which has a resistance of about 2.5 megohms is made part of the bridge network.

Amplifiers. The SND contains a preamplifier and a main amplifier and rectifier. The bolometer bridge and the preamplifier to which it is connected are housed in the scanning head. The preamplifier has a voltage gain of 50 db at 100 c from a bolometer bridge source having arms of 2-megohm resistance each. The signal is then fed by means of a cable to the main amplifier, which is in a separate unit and which has a maximum voltage gain of 100 db at 100 c.

This RC-coupled main amplifier has a built-in pulse-shaping network to take into account amplitude distortion, frequency response, and phase distortion. In order that the pulse-shaping action should be determined by the pulse-shaping plugs, it was necessary that the phase characteristics should be reasonably linear throughout the range of interest, 10 to 350 c. The frequency fall-off outside of this range should then be, in general, not greater than 6 db per octave. For the plugs used, the amplifiers were successful.

After amplification the output pulse passes through a rectifier which is connected by means of a second cable to the recorder section, located in the scanning head. The main power supply was a 24-v set of storage batteries which were recharged after 10 hours of operation from 115-v a-c or d-c sources. A third cable delivered the power to the scanning motor, to the sight when used, and also fed the output of the overall channel to the recorder.

Mounted and separately shielded on the chassis of unit B were batteries which provided bolometer bias of either 400 or 600 total volts across the bridge, in addition to filament and plate batteries for the preamplifier and bias batteries for the last two tubes in unit B. The titles on the remaining switches are largely self-explanatory. The cover of unit B was so designed that it cannot be closed unless all switches providing power are turned off.

Amplifier noises were reduced sufficiently by careful shielding and judicious selection of vacuum tubes and parts to make the Johnson noise in the bolometer bridge the limiting factor which determined the noise level.

Indicating Unit

The recorder is attached to the base of the scanning mechanism cam assembly at the rear. The signal patterns are recorded on wax paper which is drawn from a storage reel at the center of the assembly. A cylindrical platen at the top of the assembly provides the writing surface for the recording stylus which is driven back and forth across the paper by a trolley mechanism.

9.5.4 Field Tests for SND

The Fort Belvoir Tests

On the nights of January 14 to 16, 1945, the SND equipment was set up on a hill at Fort Belvoir for field tests in cooperation with the Engineer Board. On January 15, when a light rain was falling, an M2A4 and an M3A1 tank were easily detected at a range of 1,100 yards. A record of this test is given in Figure 11. Weather conditions of the kind prevailing on January 15 give a rather uniform background and it may be seen in the record that there is only one other significant signal and this was due to the top of a house. Each tank could still be distinctly recorded for a period of ½ hour after the engine had been shut off.

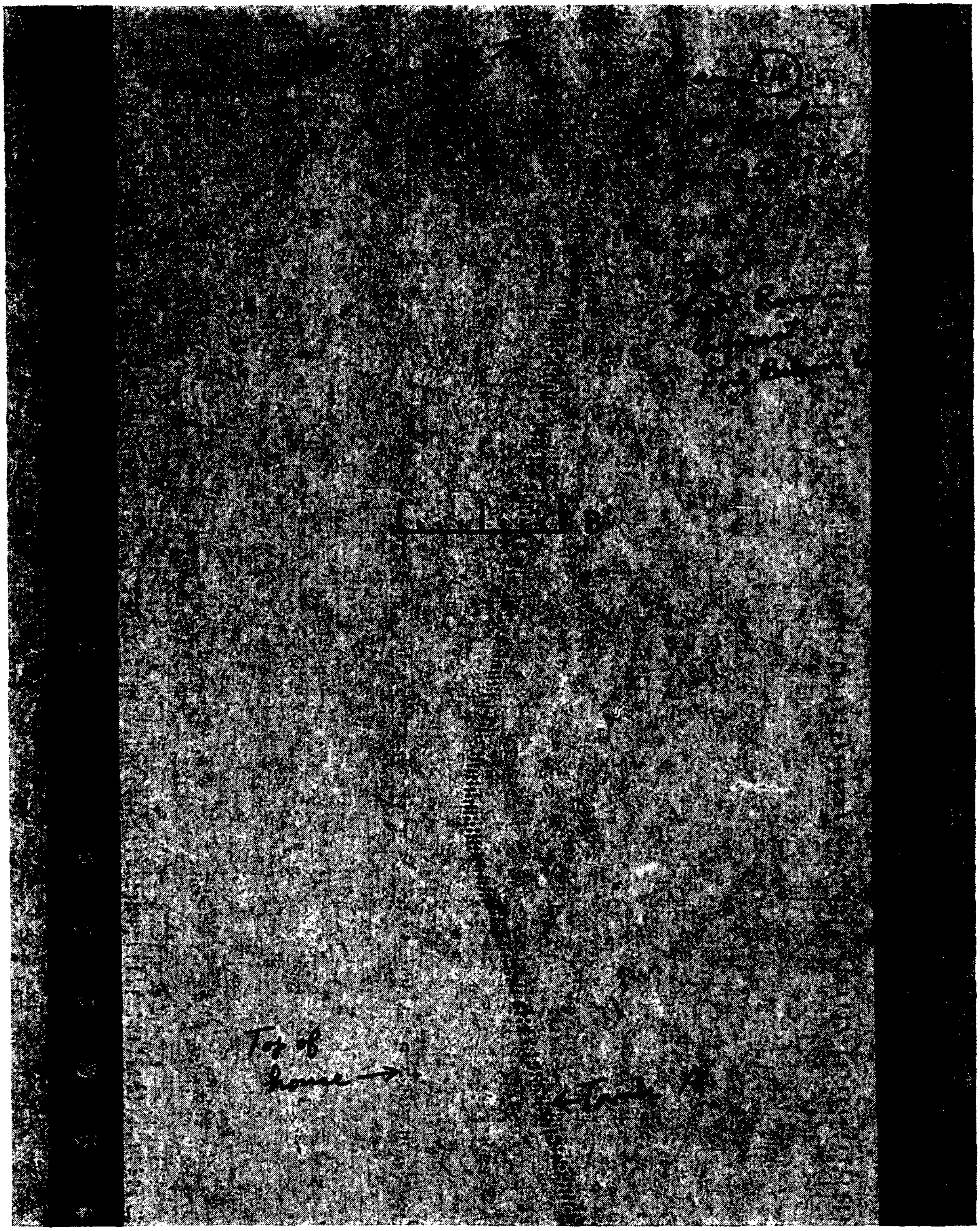


FIGURE 11. A record of Fort Belvoir tests of SND.

On a clear night the movements of the M2A4 and M3A1 tanks were recorded distinctly up to ranges of 1,950 and 1,800 yards respectively. Houses, roads, and trees gave much weaker signals than did the tanks at the same range. The rear and sides of each tank gave considerably stronger signals than the front. During these tests the movement of a ½-ton Army truck and a police car were distinctly recorded at ranges of about 450 yards.

Following the January 14 to 16 field tests at Fort Belvoir, the passband of the amplifier was modified to obtain a greater signal-to-instrumental noise ratio. Further field tests of this model were carried out on the night of February 19, 1945, at Fort Belvoir in cooperation with the Engineer Board. The movements of a medium tank were recorded up to a maximum range of 1,800 yards. However, strong signals were obtained from objects in the terrain other than tanks. This was undoubtedly due to the fact that the night was cold and clear and that there were patches of snow on the ground. As a result of the amplifier modifications referred to above, these strong signals gave long dashes on the recorder chart which interfered with the resolution of the signals from two objects and rendered the interpretation of the record more difficult.

Cape Henlopen Tests

In tests at Cape Henlopen on the nights of March 23 and 24, 1945, in clear weather at 49 F ambient temperature and 70 per cent relative humidity, the SND, land-based at an elevation of 80 feet above sea level, clearly detected the anchored lightship *Overfalls* at a range of 7,300 yards, the moving pilot boat at 6,000 to 8,000 yards, and an incoming freighter or tanker at 11,500 yards when it entered the scanned sector. Targets 0.25 degree apart could be resolved. These tests showed the desirability for possible ship detection purposes of so choosing the amplifier passband that gradual changes in temperature over the sea background would not be recorded.

Upon the basis of the experience at Fort Belvoir on February 19 and at Cape Henlopen on March 23–24 a study of the passband of the amplifier was made to obtain the best engineering compromise between the signal-to-instrumental noise ratio on the one hand and the best resolving power and simplicity of record on the other hand. In this investigation a variety of passbands in the amplifier and of input signals were used. It was tentatively concluded that amplifier characteristics were dependent upon the type of terrain being scanned and upon the type of record desired. In order to record clearly signals from small hot targets located in a terrain of gradually changing temperature, it was found desirable to design the amplifier so that the output signal would be proportional to the second derivative of the temperature with respect to distance or time. The circuit constants of the SND amplifier were modified to accomplish this. Figure 12 is a representative record of the results obtained at Cape Henlopen and was made as the SND scanned the horizon to detect ships.

Airborne Tests

The SND was tested in a PBY4 plane at the Naval Air Station, Quonset, Rhode Island, on the afternoon of March 19, 1945, primarily to determine whether it would function satisfactorily when airborne. The test showed successful airborne operation with an increase of not more than 20 per cent in the instrumental noise in comparison with ground operation. With the equipment pointed out of a side hatch on the plane and automatically scanning, each of two destroyers gave a strong record at a range of 3 miles and a surfaced submarine gave a weak signal at the same range. The shore line of Block Island gave a very strong signal, while lakes and land targets on Block Island gave moderately strong signals. With the scanning mechanism locked so that only the movement of the plane provided unidirectional scanning, the recorder was seen to operate when the line of sight crossed such targets as shore line, lakes, and land targets.

From April 19 to 27, 1945, four daylight flights and one night flight were made with the SND installed behind a silver chloride window coated with silver sulfide and located in the nose of an AT–11 aircraft furnished by Wright Field and based at Newark Airport. The airspeed of the plane was 150 miles per hour and the flights were made chiefly at an altitude of 1,000 feet, with some at 2,000 to 4,000 feet. With the angle of view of the SND pointed 15 degrees below the horizontal and with a sector 30 degrees wide and 1.1 degrees high scanned twice a second, strip records of the temperature nonuniformities on the ground were obtained. Figure 13 is representative of the results obtained

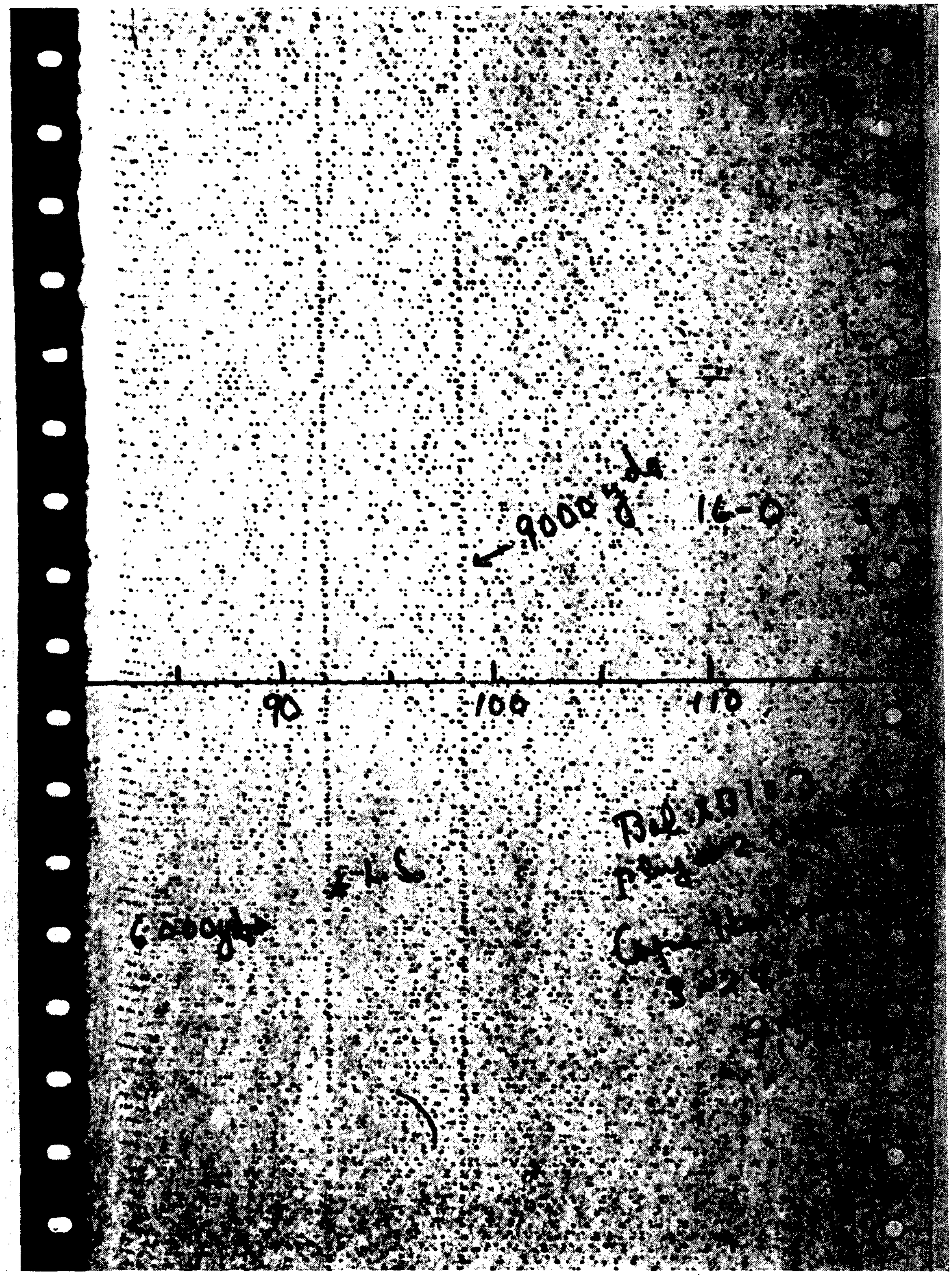


FIGURE 12. A record of Cape Henlopen tests of SND.

FIGURE 13. A survey of the Lambertville-New Hope area made with SND.

in the daytime over the Lambertville-New Hope area of New Jersey. The populated portion is seen to be full of temperature boundaries and the banks of the Delaware River also appear in the record.

At a later date more night flights were made at higher altitudes.[11] In these tests the SND scanned ahead from the same airplane at about 45 degrees from the horizontal. The airspeed was again about

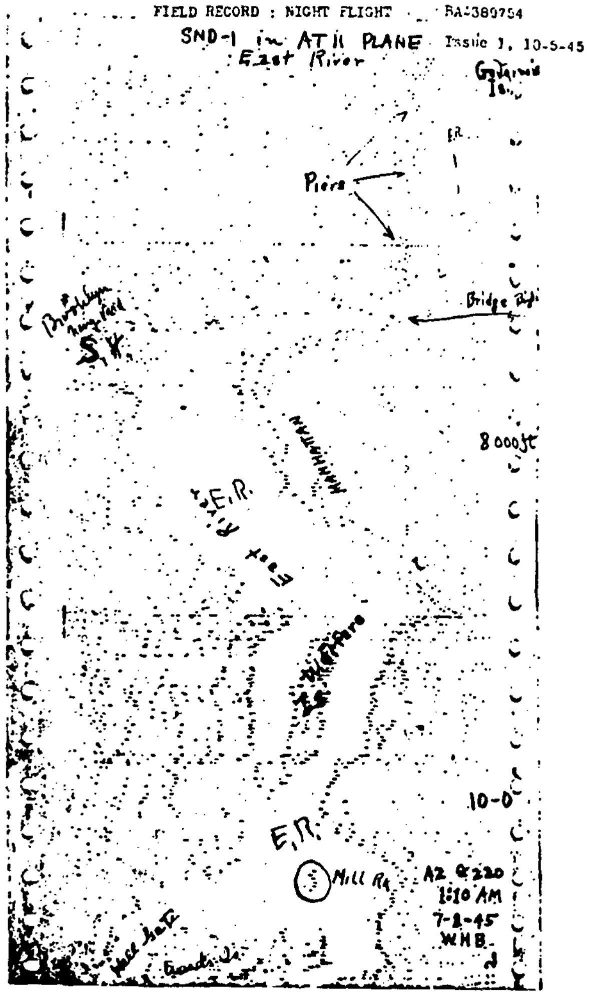


FIGURE 14. A record of metropolitan New York area made from a plane with SND.

150 miles per hour, but the altitude for the representative record of Figure 14 was 8,000 feet. This record was obtained when flying south over the New York metropolitan area in the region of the East River. The edges of prominent land masses appear in the record as temperature boundaries. This mapping was done with a bolometer having a single exposed strip. A three-lobed pulse was obtained by the use of an appropriate plug. Half-wave rectification of the center lobe only tends to give increased resolution of the various temperature boundaries, as compared with Figure 13 where full-wave rectification was involved because of the form of the bolometer used.

The results of these flights showed that the instrument noise was increased only about 20 per cent, because the SND was airborne, and that the installation (SND plus window) had an overall usable sensitivity of 6×10^{-9} watt per square centimeter from a point source incident on the reflector. In open country in the daytime, signals were received only from buildings, paved highways and railroads; the signal level was greatly reduced at night. Towns and centers of population gave numerous strong signals during the day, with large details, such as a river through a town, clearly defined, but they gave somewhat smaller signals at night. Operating factories with internal sources of heat gave very strong signals both day and night.

9.5.5 Present Status

Because of the field test results obtained with the SND, both airborne and land-based, the Army Board of Engineers has placed a pilot production order for scanner and recorder units, designed with the consultation of those working under Contract OEMsr-636 upon the basis of units used in the SND. These will be incorporated with Penrod, the Army model of the PND equipment described in Section 9.4, to provide a scanning receiver with recorder having the essential features of the SND.

9.6 THERMAL MAP RECORDER FOR GROUND SURVEY

9.6.1 Introduction

The *thermal map recorder for ground survey* [TMR][12] was developed, constructed, and flight-tested by Bell Telephone Laboratories under Contract OEMsr-636, at the request of the Army Air Forces as Project Controls AC-87 and AC-225.02. Under these control numbers were outlined the military characteristics desired, namely, to provide a scanning thermal receiver with recorder for use in aircraft to plot a thermal map for the location of suitable ground targets for heat-homing bombs.

Such a device might also find use in general strategic bombing by revealing and plotting the location of hidden factories, power plants, and transportation routes, thus furnishing part of the information required in connection with the release of bombs of various types.

This equipment plots a continuous strip map of temperature differentials or discontinuities present on the earth over which the plane flies. It can be adjusted to provide map dimensions of equal length and breadth or in which the length is some chosen factor of the breadth. The forming of the map may be observed in flight.

Flight tests have shown that a stabilized platform to reduce the mapping errors caused by the unsteadiness of the airplane in flight is essential for the formation of an accurate map.

9.6.2 General Description

The complete equipment (Figure 15), consisting of a parabolic focusing mirror, thermistor bolometer detectors, scanning mechanism, amplifier, and recording mechanism, is a single, self-contained unit, housed in an aluminum case approximately 18x18x27.5 inches, for mounting in the bombardier's compartment of a bomber-type aircraft to obtain the proper viewing angle. For this application the

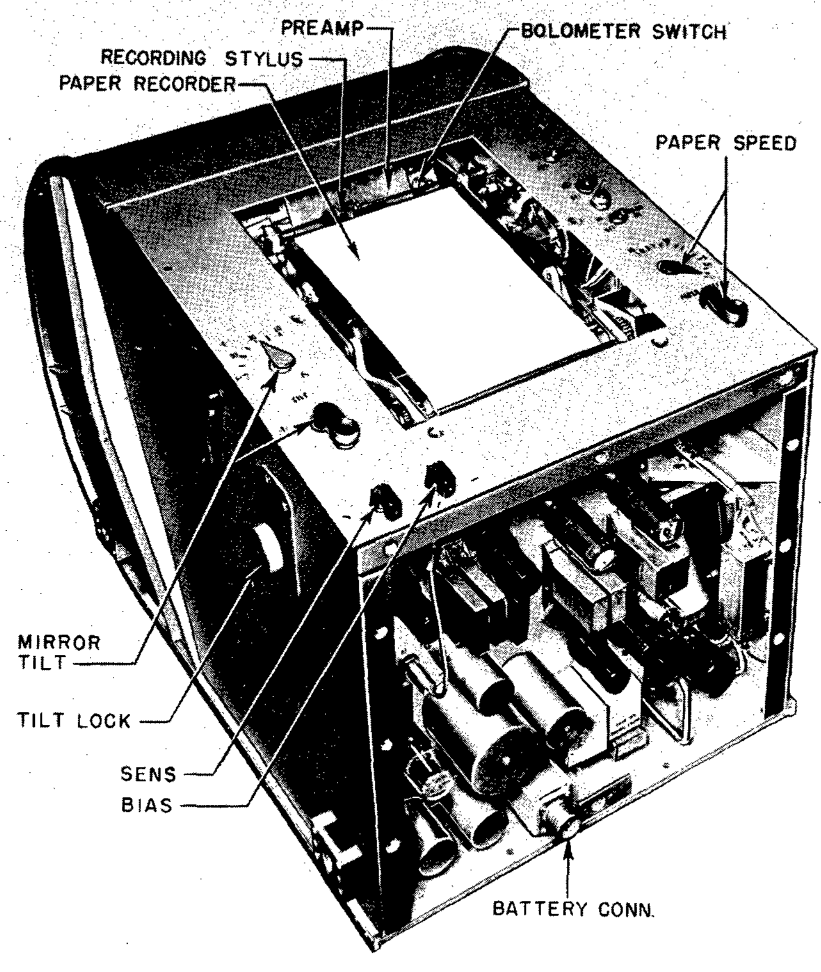


Figure 15. Photograph of thermal map recorder.

case is cradled upon a floor-mounted framework by means of antivibration supports. The case is arranged to be readily removable from its supporting framework for convenience in servicing. When mounted in the framework, the bottom of the equipment is approximately 6 inches above the floor. The total weight with mounting is approximately 85 pounds and the operation is from the 27-volt plane battery.

A 12-inch parabolic mirror is mounted in the nose of the plane, behind a suitable fixed window, capable of transmitting far infrared radiation. The mirror is scanned over a horizontal angle of 20 degrees at a rate of 60 or 120 degrees per second. Two sets of thermistor bolometer elements, mounted at the focus of the mirror, permit a choice of vertical field of view of 0.22 or 0.9 degree. The scanning mechanism can be tilted to scan at any angle from 10 degrees to 60 degrees below the horizontal.

A change in temperature of the bolometer produced by a change in the average temperature of the ground area imaged upon it produces a change in the bolometer resistance, and, therefore, by virtue of the resulting change in the d-c current flowing through the bolometer, is converted into a voltage signal. These voltage signals pass through an amplifier of special characteristics and are applied to a stylus which bears on a chemically treated paper chart 6 inches wide. The stylus is actuated by other means to move back and forth across the chart in synchronism with the scanning mirror. The amplified signals cause the stylus to plot on the advancing paper chart a map of the temperature differentials of the ground areas as they are imaged on the bolometer. The chart is so arranged that the map coordinates can be adjusted for equal specific ground distances, depending on altitude of flight, speed of plane, vertical angle of view, and scanning rate.

The equipment may be used to record hot areas against a cooler background or, by operating a switch, to record cold spots against a warmer background.

With the 0.22-degree vertical field bolometer and 6 scans per second, the minimum radiant power from a point source of heat required to produce a recorded trace on the chart is 1.4×10^{-7} watt incident on the reflector. While greater sensitivity would be obtained at slower scanning speeds, the practical sensitivity for normal mapping conditions under which a ground area is scanned only once or twice would be expected to be less than this figure.

9.6.3 Description of Component Parts

Optical System

Mirror Size and Mounting. The parabolic collecting mirror is a glass base surface coated with chrome-nickel. The mirror is 12 inches in diameter and 10 inches in focal length, and the circle of confusion is 0.4 millimeter in diameter. As shown in Figure 16, the mirror is supported in a gimbal-like mounting which permits free movement about the vertical axis and from 10 degrees to 60 degrees below the horizontal axis.

The bolometer is mounted at the focal point of the mirror and is arranged for replacement if a change is desirable. With the bolometer at this point, the vertical viewing angle is 0.226 degree for each millimeter of length of the sensitive strip and the horizontal angle of view.

Scanning and Tilt Mechanism

The scanning motion of the mirror support is produced by a cam lever attached to it which rides on a sinusoidally shaped scanning cam driven by a motor through a gear-reducing mechanism. The cam lever is held firmly in contact with the cam by means of helical springs which draw against a floating cam lever on the opposite side of the cam. The mirror is scanned over a horizontal angle of 20 degrees at a rate of about 120 degrees per second, and at this rate a point target would pass over the sensitive strip 0.2 millimeter wide in an interval of about ⅛ of the time constant of the bolometer. At the maximum rate of the sinusoidal scan, the time for one exposure will be less. It will be apparent, therefore, that some signal reduction results from 120-degree rate of scan.

The entire mirror support and scanning drive mechanism is supported in turn within a casting which is hung on centrally located horizontal bearings so that the entire assembly can be tilted around the horizontal center axis of the mirror. Tilt is controlled by the positioning of two gear rack side members which register with spur gears on each end of the tilt-control transverse shaft which is located near the upper edge of the main amplifier. This shaft is rotated by a worm and wheel under man-

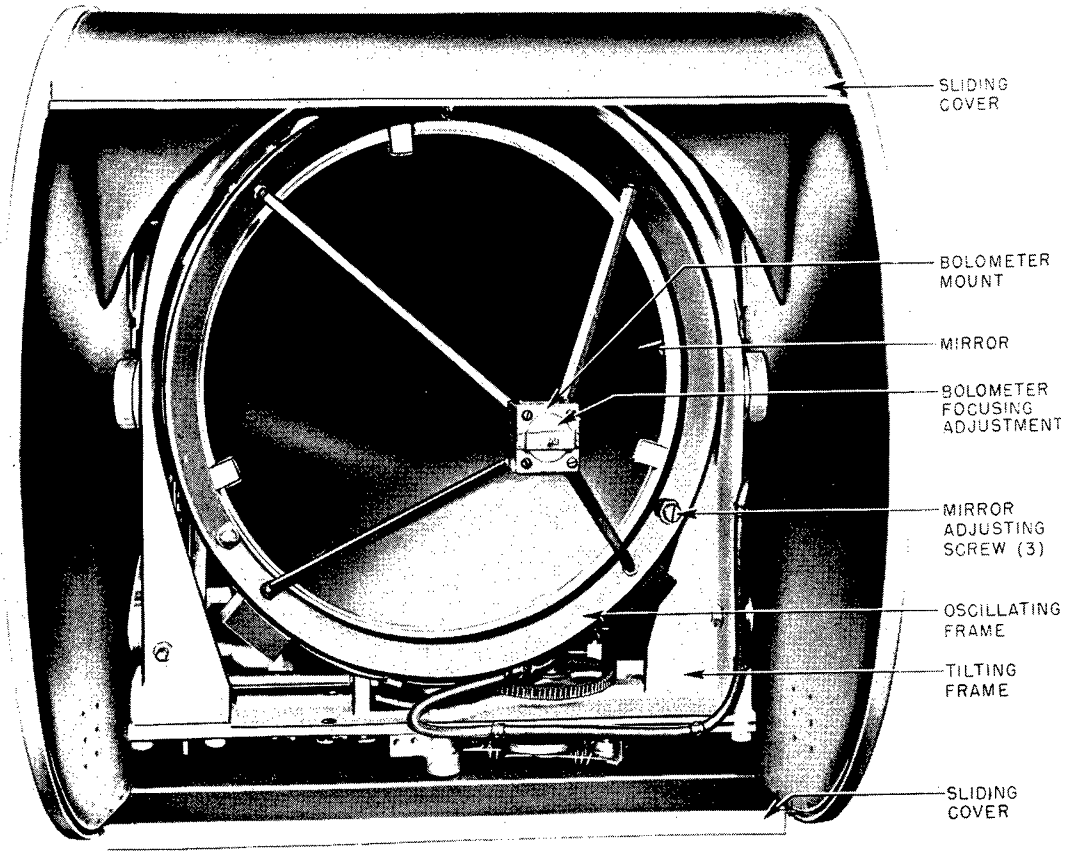


FIGURE 16. Photograph of thermal map recorder showing mirror mounting.

ual control from the tilt-adjusting crank located on the top of the cabinet on the left side. An indicator, ranging from 10 degrees to 60 degrees below the horizontal, is provided for showing the setting of the angle of tilt and this can be checked in flight by means of a spirit level mounted in a calibrated arc scale on the right side of the cabinet near the top rear.

The lateral scanning motion of the mirror in connection with the vertical viewing dimension of the bolometer results in an advancing zigzag ribbon pattern of coverage as the airplane moves forward.

Motive power for scanning is furnished by a speed-regulated dynamotor which also generates the 250 volts required for the vacuum-tube circuits. A small auxiliary permanent-magnet motor which is regulated centrifugally is provided for advancing the recording paper under the marking stylus.

Detecting Element and Amplifier

Detecting Element. Two pairs of quartz-backed thermistor strips of 4- and 1-millimeter lengths are furnished for respective vertical angular coverages of 0.9 and 0.226 degree. The strips are arranged vertically side by side in their mounting, each 0.2 millimeter in width, resulting in a horizontal viewing angle of 0.04 degree. The two strips of each pair are of equal length and connected in series with the junction between the strips brought out for connection to the preamplifier tube grid. The remaining open ends of both pairs of strips are connected in parallel to a balanced source of positive and negative d-c bolometer voltage supply. This arrangement results in a minimum d-c potential at the center grid tap which is highly desirable to reduce the possibilty of noise resulting from motion of the

grid lead connected to the bolometer. Two bolometer switches are mounted on the upper rear portion of the mirror support ring by which either bolometer can be placed in service. Although the bolometer strips are in pairs, single strip operation is employed by covering over the outer strip of each pair so that the relative change in resistance caused by incident radiation will be transmitted to the amplifier. With the bolometers of strip length as above, the total resistance presented across the high-voltage supply leads is about 3.5 megohms (terminals 3 and 4). The bolometer response-time constant is about 3 milliseconds for either pair of strips. For mapping from an airplane, a nose window, consisting of a sheet of silver chloride protected from solarization by a coating of gilsonite and properly braced to withstand air pressure, is used because of its ability to transmit infrared radiation. The loss in signal caused by this window will range from 2.5 to 4.0 db.

Amplifier. The amplifier consists of two parts, a preamplifier and a main amplifier which also contains a high-voltage d-c source for the bolometer supply. Electrically the preamplifier consists of a single vacuum tube and it is mounted on a bracket fastened to the outer stationary frame of the scanning mirror. The main amplifier has four tubes and is so designed that when used in tandem with the preamplifier a substantially equal response is provided over a band from 40 to 400 c, the response at 20 c and at 800 c being approximately 6 db lower than the peak. The preamplifier is mounted as near as possible to the bolometers to reduce the high-impedance lead length.

Connection between the scanning assembly and the stationary preamplifier is made by means of a spring which merely twists in torsion without changing its position or straining the adjacent conductors. The voltage supply for the bolometer consists of an oscillator which generates approximately 80 kc, a twin diode rectifier, and a balanced condenser resistance network circuit for filtering and stabilizing the bolometer supply, one triode of the twin-triode tube being used as the oscillator.

The oscillator output is impressed on the grid of the second triode in the tube which amplifies the voltage. A rectifying and filtering circuit in the tube output circuit produces a d-c potential across the bias potentiometer which has its positive end grounded. A maximum bias of about −120 volts is available from this source which supplements the bias of the final power tube resulting from cathode resistance drop.

The power for operating the complete device is obtained from the airplane 27-volt storage battery.

The detecting scheme consists in changing the instantaneous grid potential of the preamplifier vacuum tube by exposing one of the bolometer strips of a pair to radiation collected by the parabolic mirror and thus causing its temperature and corresponding resistance to rise or fall with respect to the unexposed strip of the pair as the radiant energy collected varies from moment to moment. If the exposed strip is heated by scanning across a hot object, the resistance of the strip decreases rapidly. If the d-c bolometer supply voltage is of proper polarity the preamplifier grid potential rises. As the scan proceeds further, the hot object is passed and the energy falling on the exposed strip decreases. The strip therefore cools, its resistance rises, and the preamplifier grid potential decreases. The signal thus produced represents a positive d-c pulse. The by-pass grid condenser and later signal-shaping circuits will not pass the d-c pulse, but instead pass it as an a-c signal. Only one-half of the a-c pulse is used in the final recording operation which is unidirectional. The bolometer supply voltage, therefore, can have the polarity set so that either a change from cold to hot or vice versa can be made to record on the paper. This feature permits distinguishing between hot and cold objects.

Some time delay is involved between the initial exposure of the bolometer strip and the final recording pulse. This is a function of the bolometer time constant and the signal-shaping circuits of the amplifier. Since a delay occurs in each direction of scan relative to the true position of the signal, some delay correction must be introduced so that signals from the same target will record in proper line in either direction of scan. This delay correction is introduced in the mechanical drive of the recording stylus.

Arrangements are provided for adjusting the bolometer voltage to the desired value for any particular unit. Depending on the particular bolometer, the d-c supply voltage as measured to ground at the load side of the series resistors will usually be within a range of ±100 to 250 volts.

Indicating Unit

The recorder is a self-contained, easily removable unit, rigidly mounted upon the U-shaped cross member in the cabinet. The recording is done near the top of the inspection window and, as the map is plotted, the paper is drawn to the lower edge of the window, thus permitting the results to be seen immediately. A standard Sangamo recorder is employed with only slight modifications of the stylus arrangement.

The standard paper provides a maximum recording width of about 6 inches. Eosin iodide recording paper as originally developed for use in Navy equipment is used. Eosin is a fluorescent chemical which permits the record to be viewed clearly in invisible ultraviolet illumination. Notes can be made directly on the paper by opening the window and using an indelible pencil on the upper portion of the exposed record, which is solidly backed by the recorder case. The paper magazine can be recharged easily by removing the inspection window from the top of the cabinet and opening the recorder case by means of two levers provided for the purpose. Access to the take-up roll can be had by removing the upper rear cover plate from the cabinet. The paper record should always be shielded from the direct rays of the sun and kept in subdued light as far as possible until thoroughly dry.

The stylus of the recorder is arranged to travel back and forth across the paper and is driven by indirect mechanical connection to the mirror shaft. Electric signals are conducted to the stylus by a sliding spring contact. The lateral motion is accomplished by translating the oscillating motion of the mirror through a set of gears to a shaft mounting the stylus drive sheave. Since the final recording signal is always produced slightly after the time a hot spot is swept over by the search beam, regardless of which direction the stylus is traveling, a backlash mechanism is included to introduce some delay in the position of the stylus with respect to the mirror position in order to get the recorded spots to line up properly at the same bearing as the stylus travels from side to side.

A small permanent-magnet motor which is centrifugally regulated, has an adjustable speed drive for advancing the paper from the magazine to the

Figure 17. Records made with TMR over Allentown vicinity.

take-up rollers. The speed setting is under control of a hand-operated crank on the upper right side of the cabinet. An indicator is provided for showing the setting of the paper speed, which may be varied from 0.055 to 0.65 inch per second.

9.6.4 Field Tests on the Thermal Map Recorder

Flight Tests

Airborne mapping tests were made from Newark Airport in an AT–11 and a B–17. The flights were made over the New York Harbor area; the lower Hudson River; the lower Raritan River; Somerville-Bound Brook and vicinity in New Jersey where a number of interesting industrial plants, highways, and railroads are found; Lambertville, which is a small town along the Delaware River; and the vicinity of Allentown and Bethlehem, Pennsylvania.

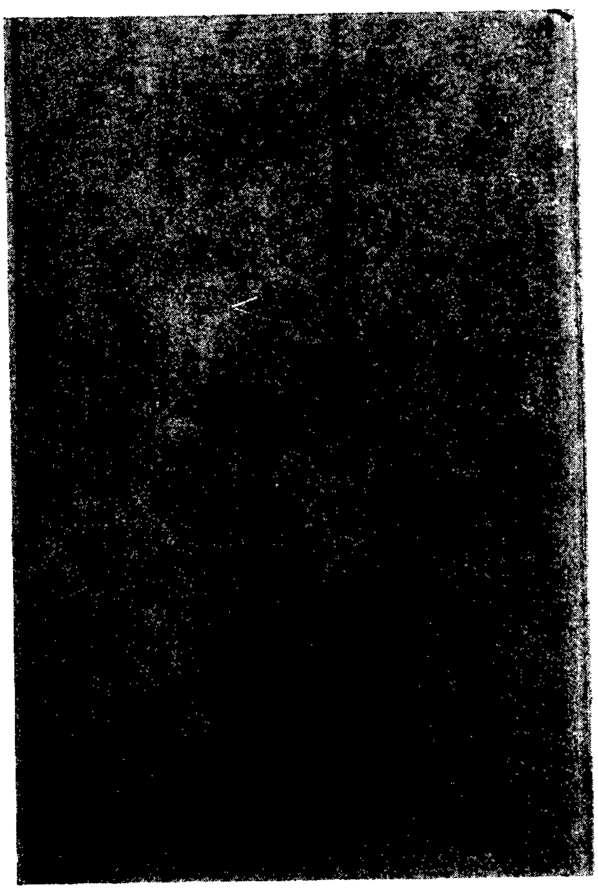


Figure 18. Records made with TMR over Allentown vicinity.

Representative maps taken during these flights are shown in Figures 17, 18, and 19.

The flight altitudes ranged from about 1,000 to 15,000 feet. Speed of flight of the AT–11 ranged between 150 and 160 miles per hour airspeed. Most flights were made between 10 A.M. and 4 P.M., but one was made between 9:30 and 11:15 P.M. All were made between April 9 and June 22, 1945.

This rather wide variety of observations was taken to gain experience with the device rapidly. To determine optimum parameters it is best to select a target area and repeat runs over it under as nearly as possible identical conditions. This was done in some cases. As a result, it was noted that settings involving increased numbers of scans of each point on the ground gave better results than fewer scans, provided there was a margin of sensitivity to compensate for the longer ranges involved in the increased coverage. In general, higher altitudes appeared to give clearer maps of rivers, roads, and relatively large targets, although clouds were opaque to the wavelengths involved and had to be avoided. Runs over a target area in one direction usually resulted in a more clearly defined map than in the opposite direction and sometimes the results were so different as to be unrecognizable. This is thought to be due to the effect of reflected sky radiation during day runs and would not be expected to be as noticeable at night. Initially, work was confined to daytime because of the greater facility of day flight work and to obtain photographic and better visual checks on performance until the best operating parameters could be established. It was then planned to make a number of night flights to evaluate performance. This plane was available for only one night flight. In all flights, however, it was obvious that stabilization of the mapper would be required to obtain accurate or, in many cases, even recognizable mapping.

In most cases a series of photographs of a target area was taken, as no one photograph gives a true mapping picture of the area because of the angle at which the photographs may be taken. Reference to the photostatic copies of maps of the area is helpful in studying the strip-map records. In most examples the dimensions of the strip map are foreshortened lengthwise to aid presentation. If the paper speed had been stepped up, the gaps between scan lines would increase so that coherence of the target features would be lost. All strip-map records

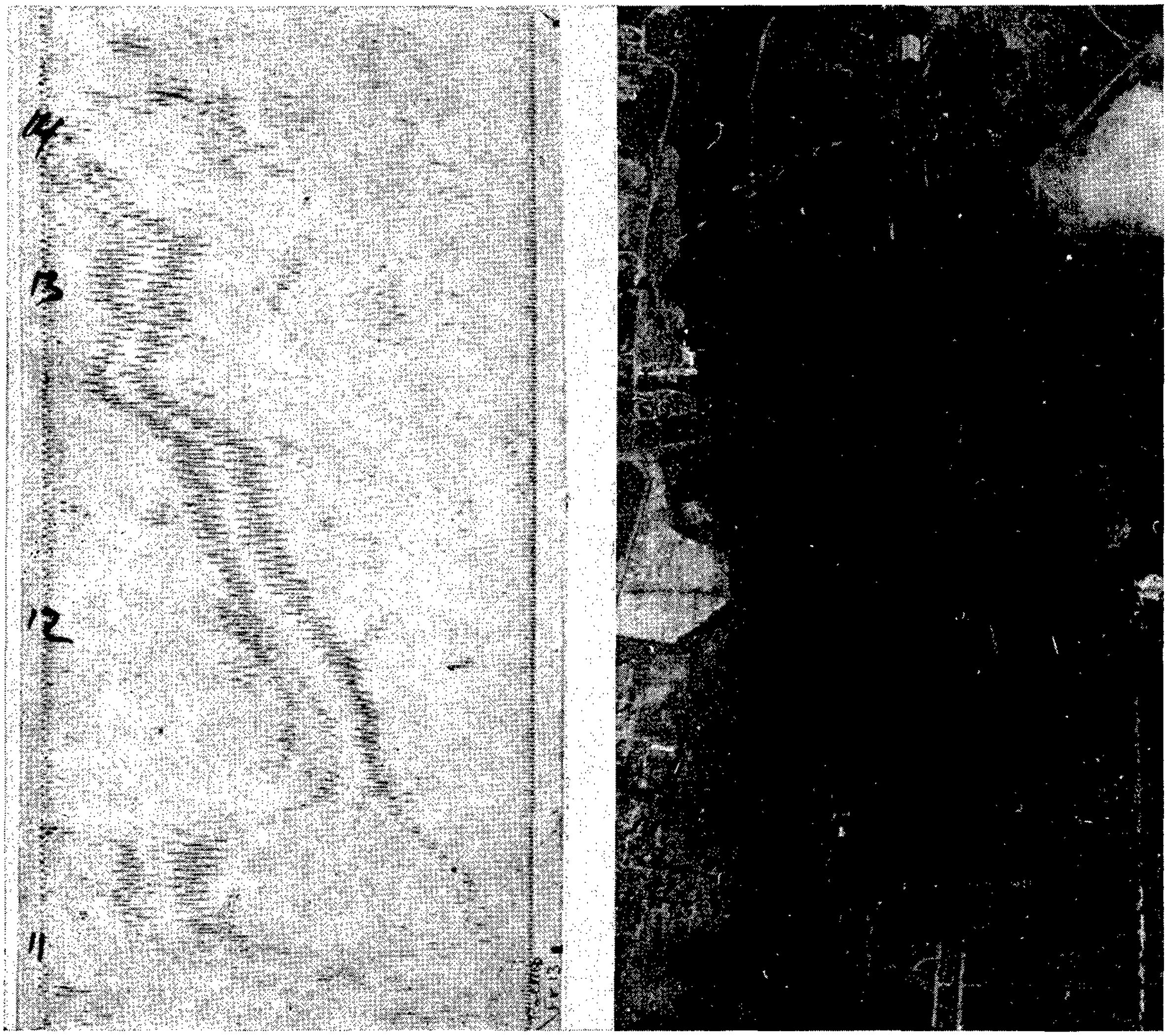


FIGURE 19. Records made with TMR over Allentown vicinity.

taken before June 6, 1945, were at the rate of 3 scans per second and all subsequent ones were at the rate of 6 scans per second, with the exception of the special Fort Knox tests mentioned in a later section.

In general it may be stated that these flight tests have shown that it is possible to map important country highways and rivers, to distinguish between open country and city areas, and to recognize various localities from the record with a knowledge of the terrain.

GROUND TESTS AT FORT KNOX [13]

On July 9–11 the TMR was tested at Fort Knox, Kentucky, in experiments with infrared detecting devices which might have tactical value to the U.S. Army Ground Forces. For these tests a special automatically tilting platform was constructed and the scanning speed was at the rate of 3 scans per second. The complete device is shown in Figure 20.

The device detected personnel and hot machine guns near cave entrances at night at the two distances tried, 300 to 400 feet and about 1,000 feet. This was in a denuded area but through partial foliage coverage in some cases. It was thought that one cave was detected solely as a cold spot. Movements of personnel could be detected readily at the distances employed in the denuded area and through partial coverage of foliage, but the device was un-

able to detect personnel or caves in thickly foliated areas. Where detection was made, angular position relative to the observation point was obtained on the record to an accuracy of a small fraction of a degree. Figure 21 is a sample of the records obtained.

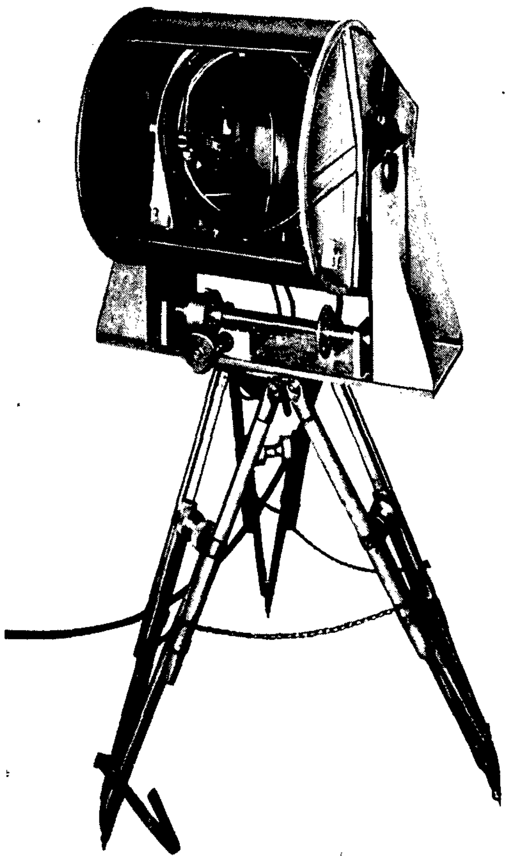


FIGURE 20. Photograph of TMR used at Fort Knox.

Tests made immediately afterward at Wright Field showed that the minimum detectable radiant flux density from a large radiating area was 6×10^{-10} watt per square centimeter incident on the reflector.

Subsequent improvements have increased the sensitivity considerably over the former value, a figure of 2×10^{-10} watt per square centimeter being obtained from a point source of fixed position relative to the mapper.

AIRBORNE TANK DETECTION TESTS AT ABERDEEN [14]

On the night of July 27–28, 1945, the TMR was tested as an airborne tank detector at Aberdeen Proving Ground. For these tests the scanning speed was 6 scans per second and the recorded strip map was three inches wide.

Tanks under way were detected and certain types of tanks gave good signals at ranges of 2,000 feet and altitudes of flight of 1,000 feet. The rear of the tanks gave stronger signals than the front. Not all types of tanks gave good signals. At greater ranges, signals were not satisfactory. The exposure time to obtain good coverage was only about 10 per cent of the bolometer time constant and, consequently, sensitivity was severely limited. A multiple element device with slower scanning rate was suggested as a way of improving range at some complication of design.

A sample of the records obtained is shown in Figure 22. It is of interest to note on these records the trace of the adjacent roadway. This was a perfectly straight concrete highway, yet it is difficult to recognize it as such, due to the unsteadiness of the airplane. These were night runs, but the altitude was only about 1,000 feet.

9.6.5 Comments on Possible Future Developments

Before the TMR can be considered a reasonably accurate airborne mapping device, a stabilized platform will have to be provided to neutralize unsteadiness of the plane in flight so that the position of the TMR may be held constant to a small fraction of a degree during mapping runs.

If a larger scanning angle were employed than the present 20 degrees, more information would be crowded into the recorded map and it would be easier to identify targets, particularly at the lower altitudes.

Flights have been made up to 15,000 feet, which may be low for tactical usage but is near the ceiling for the AT-11. It has been observed that the higher the altitude the steadier flight may be, but this is dependent upon many factors. Also night flights usually are much steadier than day. Under favorable conditions at high altitudes at night, fairly good mapping is possible without a stabilized platform, but where accuracy is essential there appears

FIGURE 21. Record obtained with TMR in Fort Knox Tests.

to be no alternative to the use of such a platform.

In general it has appeared that mapping is better at higher altitudes than at lower, entirely apart from the greater stability involved. Probably this is because the mapped areas are larger at higher altitudes and so more recognizable features of the terrain appear on the map. Of course, cloud formations between the mapping plane and earth cause portions of the map to be lost. Cloud formations

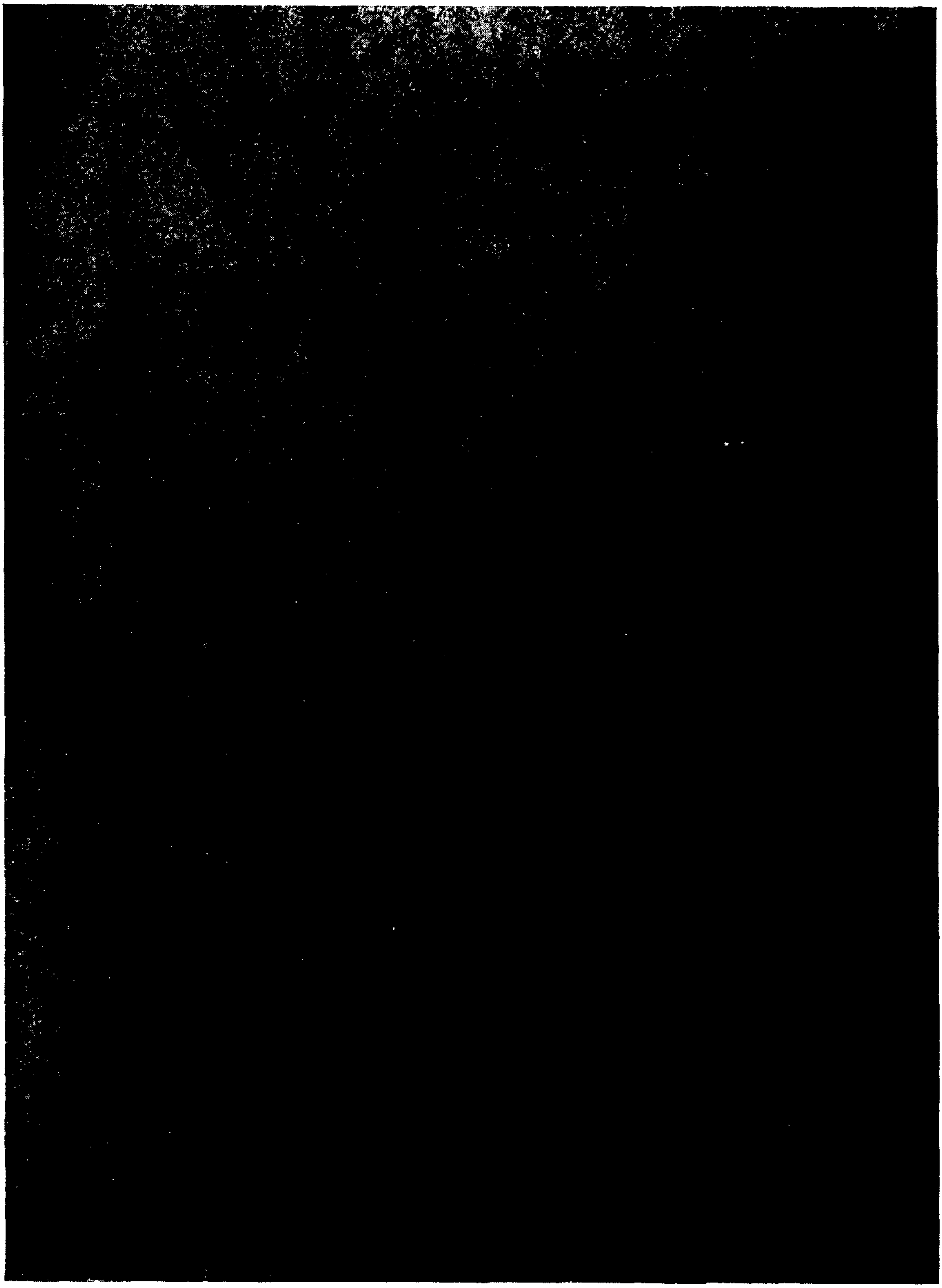


FIGURE 22. Record obtained with TMR in airborne tank detection tests.

must, therefore, be avoided. Haze merely attenuates the signals and usually can be tolerated.

The first group of flight tests appeared to show adequate sensitivity, but greater resolution seemed desirable. To overcome this the scanning speed was raised from 3 to 6 scans per second. The results were somewhat disappointing. At times, with 6 scans per second, there seemed to be inadequate sensitivity. It is clear that as the scanning speed is doubled, the exposure time, already very small compared with the bolometer time constant, is cut in half. This causes a 6-db loss because the bolometer resistance change can rise to only half as much during the target transit. Now if it is desired to retain the same ground coverage, the bolometer strip length may be cut in half. This causes a 3-db improvement because the noise power on the grid is halved, assuming, of course, that the bolometer supply voltage is kept constant per unit length. There is thus a net loss of 3 db due to doubling the scanning rate.

The decibel loss for getting detail onto the record at twice the rate seems a small sacrifice, but the records seem to show more like 6-db loss, indicating that it is chiefly the large boundaries that contribute most to the record. If this is so, and a few decibels are important, then a much slower scanning rate should be tested to find out how much can be gained by improving detail through increased sensitivity at low scanning speeds. To obtain proper coverage with the slow scanning speed, either longer bolometers will be needed or shallower depression angles must be used, thus increasing the distance to the targets. It does not seem feasible at present to increase strip length much beyond 4 millimeters unless the width is also increased beyond the present 0.2-millimeter value, because of the physical fabrication problem involved.

Reduction of the scanning speed from 120 to 15 degrees per second, or from 6 to $\frac{3}{4}$ scans per second, should increase sensitivity by a factor of nearly ten times, or 20 db. Maintaining coverage, however, will involve larger areas and point targets may not be detected so readily. This will tend to be an offsetting factor.

Another point to consider is that at the high scanning speeds signals recorded from gradual changes in temperature from one area to adjacent areas are emphasized in relation to small abrupt thermal discontinuities. This undoubtedly results in some features which cause the records to be difficult to interpret, and lowering the scanning speed substantially would reduce or eliminate this incorrect emphasis on gradual temperature differences in the scanning process. Of course, if there were sufficient margin of sensitivity, raising the low cutoff of the amplifier would reduce this effect, but at high scanning speeds such a margin does not exist. Reduction of scanning speeds has thus far been impracticable because of mechanical difficulties.

9.6.6 Present Status

Immediately prior to the termination of the war the Army Air Forces desired the TMR for further experimental use in connection with thermal mapping and bombing purposes and had opened negotiations with a commercial manufacturer for pilot models. This activity has probably been temporarily suspended, but the final laboratory model of the TMR has been furnished to Wright Field for experimental use.

9.7 THERMAL RECEIVER WITH REMOTE INDICATOR (TYPE L)

9.7.1 Introduction

At the request of the Navy Department, Bureau of Aeronautics, as Project Control NA–172, two models, A and B, of a scanning device employing thermistor bolometers suitable for installation in expendable radio-controlled aircraft (the *drone*) and two models of remote target bearing indicators suitable for use in control aircraft were developed, constructed, and flight-tested. These devices were designed to permit the guidance by remote radio control of expendable drones and the determination of their final crash dives into naval surface craft at night, based upon the instantaneous bearings of the target with respect to the drone as indicated by this equipment to a control operator. Transmission of information from the scanning unit to the indicator unit may be accomplished by a repeat-back radio link.

As by-products of this work other basic information has been obtained which is of value to the field of infrared devices, particularly those using thermistor bolometers. This includes analyses of thermistor bolometer responses to rapid traverses of

temperature boundaries; studies of amplifier design characteristics suitable for attainment of optimum signal-to-noise rendition of these responses; and development of signal treatments which provide the most definitive presentations of bearing information on cathode-ray oscilloscopes. Evaluation of the potentialities of infrared scanning devices employing thermistor bolometers, as related to speed of scan, size of collecting apertures, and angular fields of view, provides a basis for judging the practicability of proposed applications generally. Field testing experience has added considerably to the knowledge of the practical limitations imposed on infrared devices by excessive moisture, by movement of moist air masses across the field of view, and by loss of contrast between target and background when reflected solar energy is a masking factor. Airborne application has established practical requirements for the field of view requisite to the holding of a target indication in an unstabilized aircraft and has led to the development of shock-mounting techniques suitable for sensitive equipment. Considerable information relative to silver chloride viewing windows and their handling, surface treatment, and absorption losses has been gathered. The Model A equipment has been employed in an evaluation of the effect of countermeasures against infrared detection conducted by the Bureau of Ordnance in connection with an investigation of the possibilities of detection of the German *Schnorchel* by infrared devices for the Bureau of Aeronautics, and in a study of tank detection for the Army Engineer Board.

Extensive airborne tests, complemented by photographic evidence of the performance, have provided a basis for tactical evaluation. These tests have indicated that target bearings accurate to ±0.5 degree, both azimuthal and vertical, may be supplied for collision or homing course steering. Observed ranges of detection of all significant naval targets in 199 flight approaches have extended from a minimum of 2 land miles, under unfavorable daytime conditions, to a maximum of 8 land miles at night.

The final report[7] under Contract OEMsr-636 contains a full discussion of both Model A, the preliminary development, and Model B, the development finally subjected to exhaustive tests. Only Model B is considered in the description which follows.

9.7.2 General Description

Model B consists of two units: a scanning pickup and transmitting unit, and a receiving indicator unit. The scanner provides for simple harmonic scanning by a parabolic mirror 6 inches in diameter and 4 inches in focal length, at a rate of 3 scans per second. Type L employs two twin-strip thermistor bolometers mounted in a common housing at the focus of the reflector so that the total vertical field of view is 4 degrees, comprised of two partially overlapping vertical zones, each representing slightly more than a 2-degree field of view with an azimuthal sweep of 50 degrees. This unit also provides for the transmission of the derived signals and the necessary control features to a remote receiving and indicating unit. The indicator is a cathode-ray oscilloscope [CRO] the sweep of which is synchronized with the scanner. Hot targets relative to the background encountered in the upper field of view of the scanner are depicted as single spikes or "pips" above a horizontal base line; those in the lower field of view as pips below the line. The appearance of equal pips above and below signify that the target falls equally in the two fields of view. The overlapping zone is about 4 degrees. A servolink between the presentation unit and the scanner operates a reversible motor which can tilt the optical axis of the scanning head from 0 to 25 degrees to achieve the above condition. The resulting vertical bearing then appears on the calibrated dial of the indicator unit. Azimuthal bearings of targets with respect to the drone are determined directly from a horizontal scale on the face of the CRO tube. Information from the scanning unit to the presentation unit is relayed by a 4-channel carrier-frequency system. Interconnection of the two units may be achieved by means of two cables or by two radio links, one for repeat-back and the other for control.

Physically, the scanner and its associated equipment have the overall form shown in Figure 23, which provides a right-hand view. Included in Figure 23 is a front window section of the bombardier's compartment of an SNB-1 aircraft, supported with a bracket at the proper angle and position relative to the scanner. This indicates the location of the equipment when in use. Within this section is a window, trapezoidal in shape, covered with a framed sheet of silver chloride or reinforced Pliofilm.

As may be seen from the photograph, the pickup and transmitting unit forms one integrated assembly. It is well protected against shock by a single aircraft-type mounting from which it may be quickly removed for servicing. The base dimensions are approximately 16x16 inches, the overall height 17 inches, and the complete weight, 43 pounds.

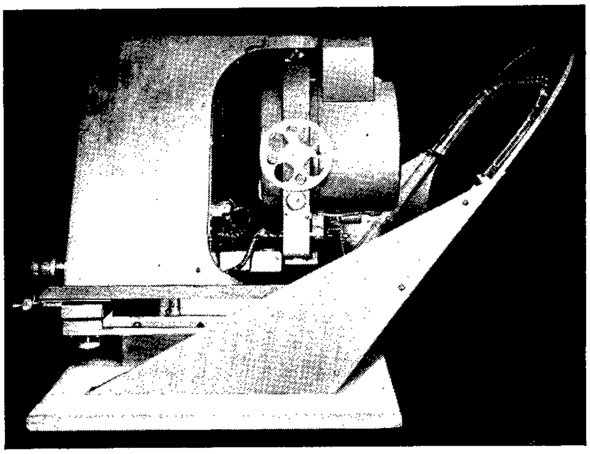


FIGURE 23. Photograph of Type L.

Likewise, the presentation unit is antishock-mounted to minimize microphonic disturbances. It is contained in an aluminum case 10x15x20 inches and weighs 48 pounds.

Power supply for the entire unit is derived from the 27-volt aircraft battery, the drain being less than 5 amperes.

Functionally, the unit may be broken down into several elements: An optical and detecting system consisting of a parabolic reflector and a dual thermistor bolometer; a scanning mechanism for oscillating this system; narrow-band amplifiers for differentiating and amplifying the signals produced by the bolometer; and the transmitting portion of a four-channel carrier system for transmitting the signals pertaining to the two vertical fields of view and for relaying instantaneous information concerning the azimuth and tilt angles of the scanning head. In addition, there is a tilt-drive mechanism and power supplies for the bolometer bias and for the vacuum-tube requirements.

The minimum detectable radiant power incident on the reflector, while scanning, is about 1.8×10^{-7} watt.

9.7.3 Description of Component Parts

Optical System

Images of distant targets are produced by a parabolic reflector 7 inches in diameter having a focal length of 6 inches, with the bolometer mounted so that the sensitive elements are at the focal plane of this collector. On axis, the circle of confusion for the image of the remote point source has a diameter of approximately 0.7 millimeter.

The reflector is affixed to a cast aluminum member which is mounted, gimbal-ring fashion, to provide for angular movement both vertically and horizontally. A spun aluminum cylinder attached to the same member acts as a shield and a diaphragm to prevent entrance of energy to the reflector from unwanted directions. The bolometer housing is fitted in a focusing mount which is anchored at its two ends to the aluminum cylinder.

Two pairs of thermistor bolometer strips, 0.2 millimeter wide and 6.5 millimeters long, mounted parallel as indicated in Figure 24 and coextensive, correspond to upper and lower zones of the field of view equivalent to 2 degrees each. A moderate overlapping of the pairs of bolometer strips precludes the existence of a central "dead" zone and facilitates the finding of targets and their centering in the

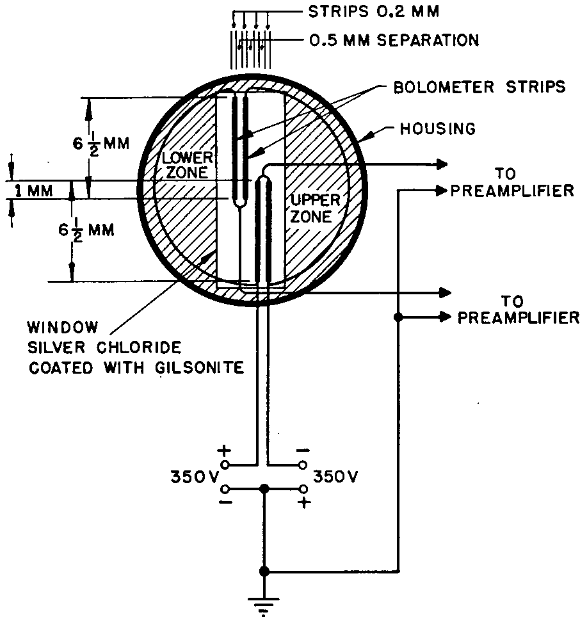


FIGURE 24. Bolometer configuration and wiring diagram used in Model B, Type L.

overall field of view. The time constants of the bolometers are about 3 milliseconds.

Scanning and Tilt Mechanism

The simple harmonic oscillation of the scanning head is achieved by a two-lever mechanism moving along the periphery of an eccentric cam, the two levers being linked by springs. One lever is simply a follower and serves only to provide uniform pressure between the cam and the working lever. The other lever actuates the scanning head through a vertical shaft attached to the yoke-shaped aluminum casting within which the optical system is mounted in crosswise pivots. A ball-bearing roller is employed as the point of contact between the working lever and the hardened steel cam, but for the sake of smooth operation a shaped block of oilite bronze is used with the follower lever. The scanning rate is about 150 degrees per second. The variation of scanning speed with angle in the vicinity of the reversal points is overcome by the provision of a 50-degree scan of which only the central 40-degree range is indexed for readings of azimuth on the presentation equipment.

The driving power is derived from a speed-regulated dynamotor which serves also to supply a 250-volt d-c output for plate supply to the vacuum-tube equipment. The dynamotor is operated on a standard 27-volt aircraft battery supply and rotates at a speed of 7,200 rpm.

When scanning, successive images of the elements of the panorama are swept across the strips of the bolometer. In the simple case of a point discontinuity in the energy received from an otherwise uniform background, the passage of the image across the first of the two strips occasions a heating (or cooling) of the bolometer strip. The result is a small change in resistance and, since there is a d-c voltage biasing the strips, a corresponding decrease (or increase) occurs in the voltage drop along the strip. As the image passes beyond this strip, the resistance, and hence the voltage drop, begin to return to their former values. However, as the image enters the second strip, similar but oppositely directed voltage changes occur (due to opposite polarity of the d-c bias). As a result, the rate of change of the potential at the junction of the strips is the sum of the changes due to the cooling of the first strip and the heating of the second. Finally, as the image emerges from the second strip, the resistances and voltage drops across both strips return to normal. There results, therefore, an a-c signal of a definite characteristic spike-like waveform. Since on the return scan the senses of the voltage changes are reversed, the shape of the signal obtained is also reversed. When the target is nearby and large, two such signals are obtained, one for each boundary.

The amplitude of the signal derived from the scanning of a target depends not alone upon the energy focused upon the bolometer strip as determined by the size and temperature of the target, the diameter, focal length, and precision of the mirror, and the dimensions of the bolometer, but also on the basic sensitivity of the bolometer, the bias voltage, and the relationship of the bolometer time constant to the rate of scanning. With a 150-degree per second scanning rate, the time of traverse of the 0.2-millimeter strip is of the order of 1 millisecond. Since the time constant of the bolometer is something over 3 milliseconds, it is apparent that the high scanning speed is obtained at the cost of a substantial signal loss. This may be regained when bolometers of shorter time constant become available.

A tilt mechanism is provided to point the receiver toward its target. This mechanism consists of an arm attached to the pivoted optical system which is provided with a roller. This roller follows the curved slot of the cam, thereby varying the tilt of the scanning head. The cam shape is such that the rate of change of the angle of tilt increases continuously as the downward tilt increases. This facilitates the tracking of a target during a level flight approach. The shape was arrived at by consideration of the actual rates of change in vertical target bearing for level flight approaches at various possible elevations and speeds.

If the missile were approaching its target in level flight, the indicator would show a signal wholly or predominantly below the horizontal line in the observing screen. The scanner would, therefore, have to be tilted downward until an equal signal above and below the horizontal line would be registered, indicating that equal amounts of energy were received from the target by the upper and lower bolometers. If the required tilt were exceeded, the signal would appear predominantly in the upper field of view, indicating a need for an upward tilt of the scanning head.

Control of the tilt is achieved by a relay system at the pickup unit which translates the control instructions to reversals of the tilt-drive motor.

Amplifiers and Carrier System

When dual bolometers corresponding to two separate zones of the field of view are used, the succeeding electronic equipment must also be in duplicate, providing two distinct signal channels. In each of these channels there are 3 stages of amplification preceding the modulators which form a part of the carrier system which permits a single radio path to link the transmitting and receiving unit of the equipment.

The amplifier for each channel consists of two sections, a preamplifier and a signal amplifier. The preamplifier is a single-stage type and is located close to the bolometer in a housing on top of the cylindrical shield of the optical system. Hearing-aid tubes, selected to minimize microphonic disturbances, are used in the preamplifier.

Preamplifier components are rigidly fixed to an aluminum chassis which is antishock-mounted on sponge rubber. The period of this mounting is sufficiently low to avoid microphonic noise contributions by the amplifier tubes. Connections from the amplifier panel to the bolometer leads and to the other outgoing circuits are by means of short flexible links of multistranded wire. Arranged to have very low capacitance to adjacent grounded surfaces, these links do not create noise. Overall, the microphonic response of the system to the periodic vibration of the scanning mechanism should be no more than barely detectable in the thermal noise pattern as viewed at the output of the amplifier with an oscilloscope.

Since the thermistor bolometer is a high-impedance device, the paralleled resistance of the two strips of one of the bolometers in this equipment being of the order of 4 megohms, it is important that the input impedance of the amplifier be high if signal attenuation is to be avoided. To insure against the flow of grid current and the reduction of this high-input impedance, a 1-volt Mallory bias cell is employed. (The use of the bias cell has avoided a small amount of further development effort. It undoubtedly could be eliminated with further work.) Use of relatively large grid blocking condensers (0.01 millifarad) assures that the input resistance is essentially that of the paralleled bolometer and grid leak resistances, thereby rendering the thermal-noise threshold a minimum.

The preamplifier is linked by flexible cables to the stationary panel on which the remainder of the electronic equipment, including the signal amplifier, is located. This amplifier is a conventional two-stage amplifier using type 6SJ7 tubes.

Flexible cables link the preamplifiers through a plug-in connection to the stationary panel on which the remainder of the electronic equipment is mounted. Second and third stages of the signal amplification are mounted at the top of this panel and employ type 6SJ7 tubes. The choice of the grid coupling condensers for the second stages, however, is such as to provide a differentiation of the signals.

The differentiated signals are characterized by prominent and symmetrical pips corresponding to the crossovers of target images from one to the other of the twin bolometer strips. It is these pips which are ultimately employed in the presentation of target bearings on the indicator unit.

High-frequency response of the signal amplifiers is restricted by the use of shunt capacitances. The cutoff is sufficiently high to prevent appreciable signal attenuation, but the higher frequency components of the thermal noise background are eliminated, thereby enhancing the signal-to-noise ratio. The overall frequency response, as determined by the differentiating elements and the shunt capacitances, is such that peak gain occurs at 80 cycles, the gain being 6 db lower at about 20 and 200 cycles.

Gain control potentiometers are provided between the second and third stages of the amplifier to permit adjustment of the two-channel gains to the same value. Overloading of the system by the huge input signals of nearby targets is prevented from blocking the final amplifiers by the inclusion of 5.6-megohm resistors in series with the grids. A similar provision is made for the grids of the modulators. Overloading of the radio link, which would result in interchannel modulation, is precluded by a limiting action in the signal channel modulators.

In order that a single radio link on a single pair of wires may convey all the necessary information from the scanning device to the presentation equipment, four carrier frequencies are employed, 21, 17, 13, and 9 kc. These frequencies correspond respectively to the signals produced by the lower and upper bolometers, the azimuthal position of the

scanning head and the vertical tilt of the scanner. A four-channel band-pass filter couples the channels to the outgoing line, effecting, at the same time, an impedance transformation from a 100,000-ohm to a 50-ohm level.

The carrier frequencies are generated by conventional LC oscillators, the 17- and 21-kc oscillators employing the separate triode units of a single tube. For the 9- and 13-kc oscillators, separate tubes were used, the two-triode units of each being joined in parallel.

The modulators for the signal channels are two-grid tubes where the signal frequency is introduced to the first of the control grids and the carrier frequency to the second. Since, with this type of modulator, there is a translation gain, these tubes may be considered also as providing a part of the signal amplification. Modulation is principally downward; with sinusoidal input producing 100 per cent downward modulation, the upward modulation is about 50 per cent. Larger signals which cause considerable downward overmodulation do not produce any appreciable increase in peak carrier output. This limiting action safeguards against the overloading of the succeeding radio link.

Modulation of the azimuth and tilt channels is by means of potentiometers geared to the scanning yoke and the pivoted optical system, respectively. The voltages derived from these potentiometers and applied to the band-pass filter are directly indicative of positions. At the receiving unit, the demodulated output of the azimuthal channel is employed directly for controlling the horizontal sweep of the cathode-ray indicator tube which is thereby synchronized with the scanner. The tilt channel provides one link of a servo system by which the tilt is controlled from the receiving position.

Bolometer bias voltage is derived from full-wave rectification of the output of a high-frequency oscillator. A high step-up ratio between the oscillator coil and the pick-off coils provides a terminal voltage of 1,000 ±500 volts. An RC network filters this supply and drops the voltage to that which may safely be applied as bolometer voltage, i.e., about ±350 volts.

PRESENTATION UNIT

Figure 25 shows a view of the presentation unit which is contained in an aluminum case, 10x15x20 inches long. The case is antishock-mounted and weighs 48 pounds. The connecting cables are attached on the front panel as is the practice for airborne equipment. The controls and adjustments and the viewing face of the cathode-ray tube are also located on the front panel.

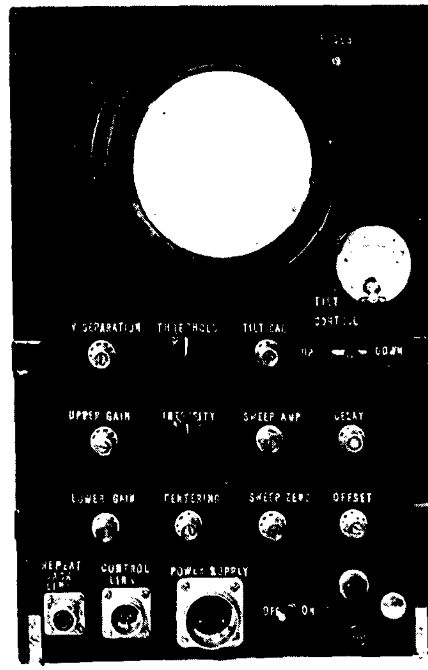


FIGURE 25. Presentation unit for Type L.

The azimuth angle of a target signal may be read from a scale on the face of the cathode-ray oscilloscope and the vertical angle of the target may be determined from a meter. The sweep of the cathode-ray tube is synchronized with the motion of the scanning mirror and is controlled through one of the four carrier channels discussed in the preceding section. The signals arrive at the presentation unit along two others of the four channels and manifest themselves on the cathode-ray screen in such a way that upper and lower fields of view render pips on the screen above and below the horizontal axis of the tube, respectively.

9.7.4 Recent Modifications in the Type L Equipment and the Effects upon Sensitivity

Repeated bolometer failures, which were seemingly attributable to the difficulty of fabricating units with relatively long and narrow strips of

thermistor material, led to the substitution of a new reflector of 4-inch focal length for the 6-inch one in the scanner. In addition to the one-third reduction in the strip lengths of the bolometer elements which this change permitted, the strips were increased in width from 0.2 to 0.3 millimeter. The changes have now been completed and five of the new type bolometers have been received. The unit has also been refinished with black crackle lacquer.

The new reflector has a diameter of 6 inches compared to the 7-inch diameter of the former collecting surface. Other things being comparable, this would have resulted in a reduction in threshold sensitivity in the ratio of the areas of the two reflectors. Upon measurement, however, employing a bolometer of the original type in both cases, the sensitivity proved to be higher with the smaller reflector, indicating a considerably greater optical merit. The new reflector is of glass, gold-surfaced, while the former unit was an electro-deposited replica with a rhodium surface.

Changes in the strip dimensions of the bolometers, which were such as to maintain nearly constant areas, would not be expected to introduce any appreciable change in sensitivity, assuming that the bias voltages were adjusted in the two cases for equal power dissipation per unit of area. Comparative sensitivity determinations with the old and the new types of bolometer, employing the new reflector in both cases, appear to substantiate this. The bias voltages applied to the two bolometers in these tests were not in the proportion of the strip lengths, a nonlinear regulation in the bias supply preventing the application of as high a voltage to the new unit as would be permissible. As a result the sensitivity figure with the new bolometer was lower but by almost the amount that would be predicted.

The net result of the change in reflectors and in bolometers, with the highest conveniently available bias applied to the new bolometer, was a negligible change in sensitivity. A small increase could be obtained if the bias voltage were to be made higher. The actual sensitivity figures are found in Table 3.

Sensitivity measurements were made as follows: A target, masked but for a small aperture, was operated at a temperature about 270 centigrade degrees higher than the background, so high as to render all incidental background discontinuities small by comparison, thus avoiding one of the principal difficulties of this type of measurement. The aperture of the scanner was then reduced by sector masks until the signal due to the target could just be detected in the random noise pattern as viewed on the CRO tube of the presentation unit. The area of the reduced aperture was measured and the radiant energy reaching this area from the target was computed. This, divided by the total area of the reflector, yielded the figure for the minimum radiation density detectable by the device as normally operated without the aperture masks. The use of sector-shaped masks properly weighted the rays reflected from the various radii of the mirror, and so was a truly proportional sample of the entire reflecting surface.

TABLE 3. Sensitivity data on Type L.

Reflector	Bolometer	Minimum detectable radiation density
Old, 7 in. diameter, 6 in. focal length	Old, 6.5 by 0.2 mm strips, 450 v bias	1.1×10^{-9} watt/cm^2
New, 6 in. diameter, 4 in. focal length	Old, 6.5 by 0.2 mm strips, 450 v bias	0.8×10^{-9} watt/cm^2
New, 6 in. diameter, 4 in. focal length	New, 4.5 by 0.3 mm strips, 250 v bias	1.0×10^{-9} watt/cm^2

9.7.5 Field Tests of the Thermal Receiver with Remote Indicator

For airborne tests of the Model B of the thermal receiver with remote control system, an SNB–1 aircraft, 29885, was assigned to the project by the Navy Bureau of Aeronautics. Installation of the equipment was made at the Naval Air Modification Unit [NAMU], Johnsville, Pennsylvania, starting January 11, 1945. Installation included the substitution of a new front nose section with a silver chloride insert, mounting of the scanning unit in the bombardier's compartment, and the placement of the presentation unit in the cabin, together with the necessary intercabling and power supply connections.

Synchronous photography of targets and of the corresponding indications of the infrared equipment proved to be a rather intricate problem. However, circuit modifications were made in the presentation unit itself to actuate relays which would trigger the cameras at each limit of the scan. Attached to the presentation circuit was a micropositioner polar relay, operated in series with the like relays employed for reversal of pip polarity at

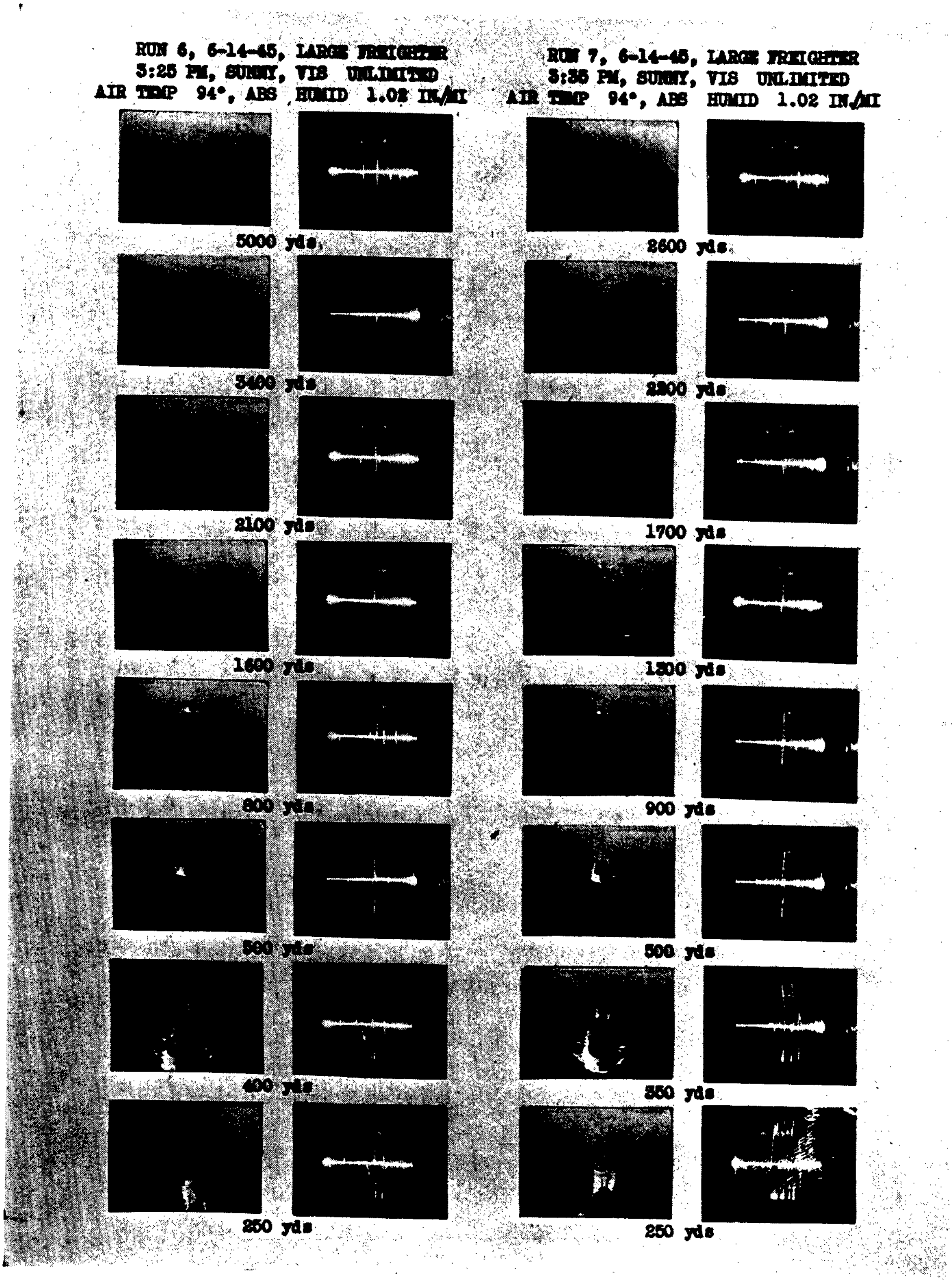


FIGURE 26. Typical record showing performance of Type L.

the limits of the scan. The contacts of this relay, together with a battery lead, were brought out to a connector on the panel to which was connected an auxiliary camera control box. The normally closed relay in this unit was released momentarily at the beginning of each scan, during the brief reversal of the polar relay, and served through its back contacts to trigger the two-camera solenoids. Careful relay adjustment was required to achieve the action at a proper time. For movies, power could be applied continuously to the camera solenoids by a switch.

The camera in the nose was set to have its shutter normally closed and was opened at each trigger pulse for a time dependent upon the setting of the frame speed governor. The lens on this camera provided a photographic field of view of about 27x39 degrees, the former being closely like the vertical tilt range of the scanner and the latter being almost the scanning range. Hence, with a mounting that brought the top of the field of view barely above the horizon when in flight, the camera recorded positions of targets consistent with those indicated by the infrared equipment.

In the camera employed for CRO photographs, the shutter was set to be normally open and the governor was adjusted for maximum speed so that the film transfer was made quickly. Hence this camera recorded on each frame all that transpired during a particular complete scan. A lens which was adjustable to focus down to less than 12 inches was used.

Photographic Records of Target Approaches

Starting at NAMU on May 14, 1945, preparations were made for the synchronous photography of targets and of the corresponding CRO indications of the equipment. Several techniques had to be tried before satisfactory results were obtained, and several flights were required to establish proper parameters for the camera settings. The final procedure involved the simultaneous triggering, at the end of each scan of the search equipment, of a camera mounted in the nose of the plane and another focused on the CRO tube. The shutter of the nose camera was normally closed, that of the CRO camera normally open. The result was a target picture corresponding to the start of each scan and a CRO picture which recorded all target indications produced within that scan.

Photographic records of more than 60 target approaches were made, though repeated shutter failures in one or the other of the cameras vitiated about half of these for analysis or reproduction. Typical of the useful records are the selections shown in Figures 26 to 29, inclusive, representing all or part of about 20 runs on random ship targets, nearly all of which were freighters.

As explained in Section 9.7.3, target indications are indicated in the form of sharp pips on a CRO screen, targets in the upper half of the 4-degree vertical field of view being presented above the horizontal axis and targets in the lower half below, a symmetrical pip designating a target centered in the field of view. Tilt of the scanning head by remote control from the presentation unit permits such centering. A scale of azimuth, inscribed on the face of the CRO, as shown in the photographs, designates the target bearing within a ±20-degree range. A meter adjacent to the CRO indicates the tilt of the scanner and hence, for centered pips, the vertical bearing of a target. A threshold control in the presentation unit permits the suppression of CRO indications produced by noise of lower level than the signals. Generous use of such suppression was made in the photographic runs, partly for the sake of clarity. With less suppression, an experienced operator could distinguish target indications well down in the noise level and hence at greater ranges than those photographed. For this reason, the conditions set up for these runs are more representative of the ranges attainable for robot-control devices not possessed of intelligent discrimination, and such was the intent.

With the above description of the operating features of the equipment, it is believed that the photographed target approaches are otherwise self-explanatory, visibility, time of day, and weather conditions having been noted for each. Sharpness of the angular position indications is apparent and rough judgment may be made of the true bearing accuracy by comparison of the target and CRO photographs, since the target camera embraced a horizontal field of view differing by less than 1 degree from that of the scanner. However, misalignment of the nose camera sometimes shifted its axis a bit to the right or left of center. The complicated patterns on the CRO at close approach to the target may be correlated in many cases with deck and superstructure features of the targets, and where the approach was oblique this may be detected in the

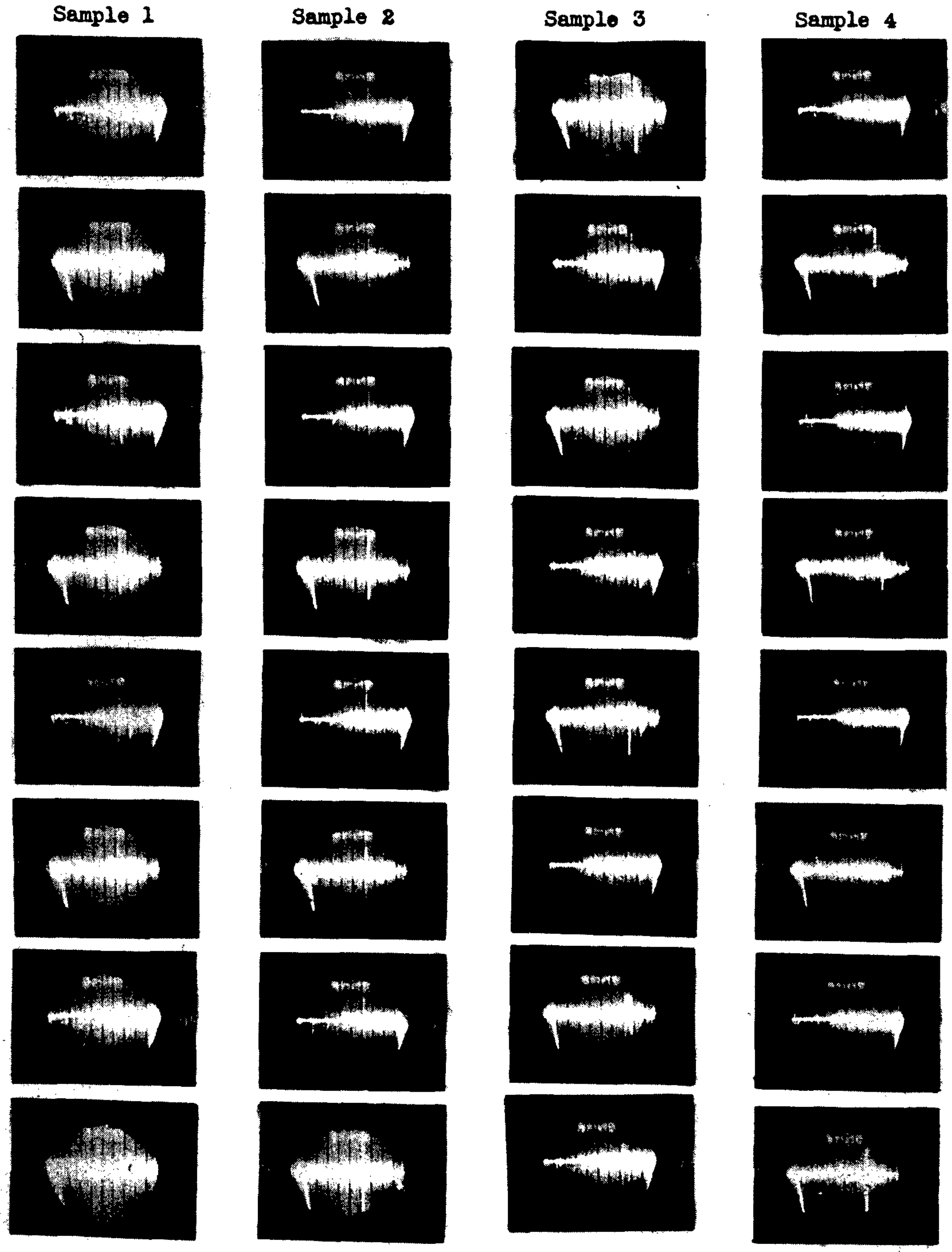


FIGURE 27. Typical record showing performance of Type L. These illustrations show a fading effect in infrared transmission. Scan by scan variations (⅓ second intervals) in the target indications due to a freighter 1 to 2 miles distant, observed from a shore location at Cape Henlopen, 11:20 A.M., June 28, 1945 with Model B of Type L Nancy equipment.

indication by its slanting coverage of the upper and lower halves of the field of view. Thus, a sort of crude television exists.

Not demonstrable in a selection of 8 pictures from camera sequences which ran to as high as 200 or more frames is the degree of continuity of target-bearing indications. Analysis of a number of the complete films has shown this to average 75 per cent and to be as high as 95 per cent. In operation, the continuity appears to be even better than this, due to the use of a CRO with a high-persistence screen. Photographs lose this illusion by reason of the smaller latitude of the film relative to that of the eye and discrimination of the film against the weaker green persistence pattern relative to the blue initial trace. In a robot device, a "clamp" circuit could provide the memory feature of the persistent CRO screen, maintaining a missile on course during short gaps in information, such gaps disappearing at the closer ranges. A robot, incidentally, would have achieved a better result in vertical control than the human operator with his slow reactions was capable of attaining in the samples of photographed runs.

Night Flight Experiences

Five attempts at night flights were made from NAMU between June 7 and 22, a number of other scheduled flights having been canceled due to weather conditions. Without night-landing facilities at that station, it was necessary to land at the Willow Grove Naval Air Station [NAS], several miles removed. Not only was this cumbersome but, with a considerable flying distance to target areas, and the difficulties of locating chance targets at night, operations on this basis were impractical. Dependent only on dim running lights, a pilot could not distinguish a ship target at sufficient distance to establish a run that would serve to evaluate the range of the equipment. (With a 4-degree vertical field of view and a 40-degree sweep, the equipment is not of itself a primary search device.) At the ranges of one mile or so at which runs were usually started, large signals were obtained from a number of vessels, and, in the dusk and dawn periods when targets could be located, representative range performance was obtained.

Following this experience, a request was made to the Bureau of Aeronautics for a specific target vessel, preferably a naval craft, to operate in a designated area and to bear lights adequate for distinguishing its presence from an aircraft at 5 or more miles distance.

Learning of a special target ship aground in Massachuetts Bay, the Bureau of Aeronautics arranged for tests from the Squantum NAS. This ship, the *Longstreet,* was equipped with artificial deck heating, about half of the deck area being surmounted by steel plates which could be heated by oil burners. Used by the Bureau of Ordnance for high-angle approaches in tests of other infrared devices, this target proved unsuitable for low-altitude runs by reason of the horizontal disposition of the heated area. As shown in Figure 28, close approach to the *Longstreet* in low-level flight produced large signals, much larger in fact than from normal targets, even long after the heat had been shut off. However, the signal intensity decreased with distance at a much faster rate than in runs on operative vessels, due to the small vertical component of heated area. Hence, it was decided that this target was of no use for evaluation of this type of equipment. In deciding this, runs were made both by day and by night and with different amounts of deck heating.

Sample photographs, Figure 28, of runs on the *Longstreet* include selections from a complete daytime run, made at 4 P.M., July 13, one and a half hours after heat had been shut off following the heating of the entire deck area. Under this condition the target indications probably were due largely to the contrasts of reflected solar energy from the target and the background and the run is fairly comparable to many others. Target crossover pictures for two runs at around 3:15 P.M. on July 12, 45 minutes after the cutoff of total deck heating, show much stronger signals, full threshold suppression having been employed in the presentation unit. Samples of CRO frames (Figure 28) from two night runs on July 12 made around 10:15 P.M., 15 and 25 minutes after the heating of one 8x80-foot section of the deck had been cut off, show the more rapid attenuation of signal with distance than is experienced with normal targets. The first run was made at 300 feet altitude and the second at 600 feet.

Cape Henlopen Tests

With the Type L equipment installed on a tower of the Surf Club at Cape Henlopen, Delaware, adjacent to a Bureau of Ships infrared test station,

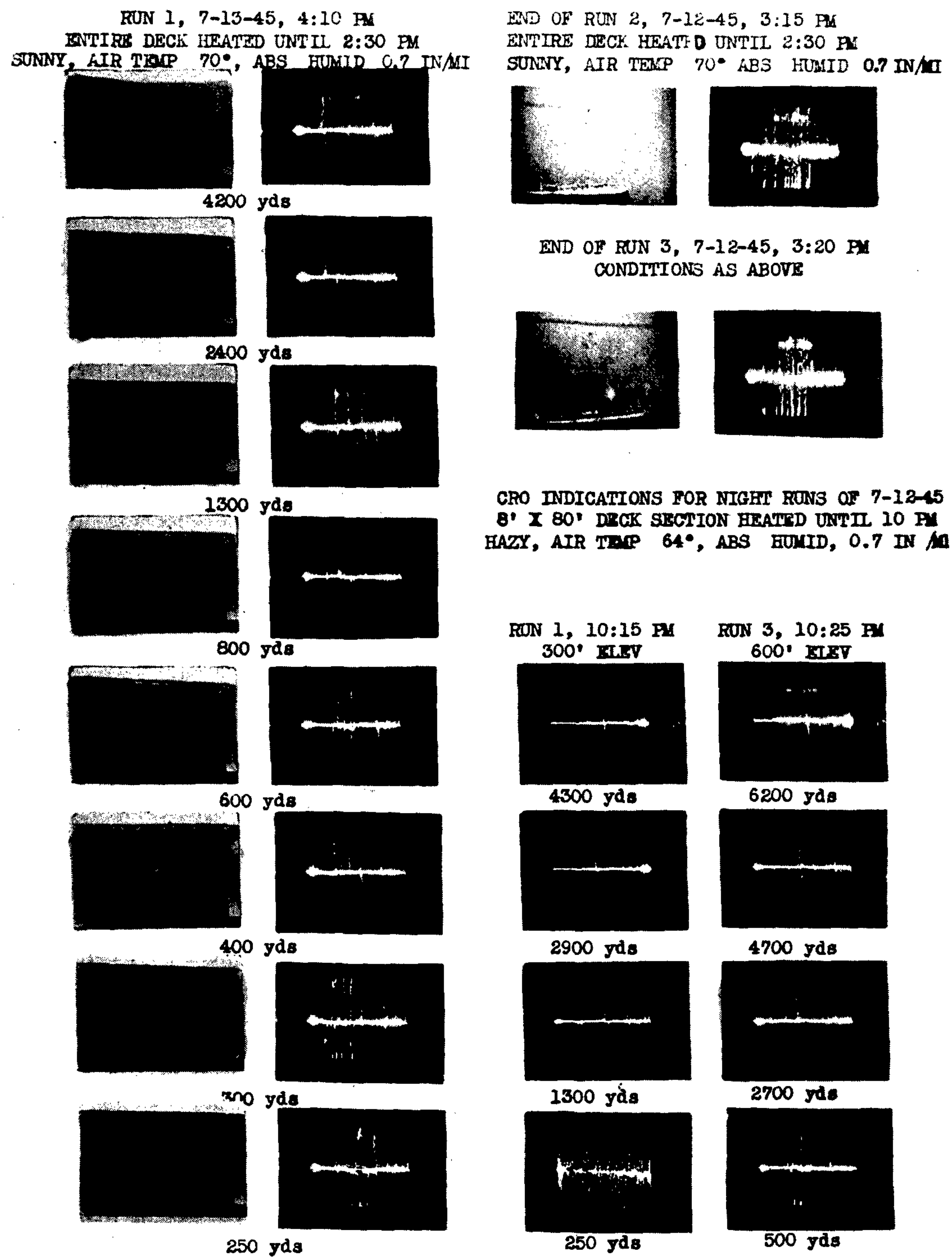


FIGURE 28. Typical record showing performance of Type L in flight approaches to the Longstreet, an artificially heated target.

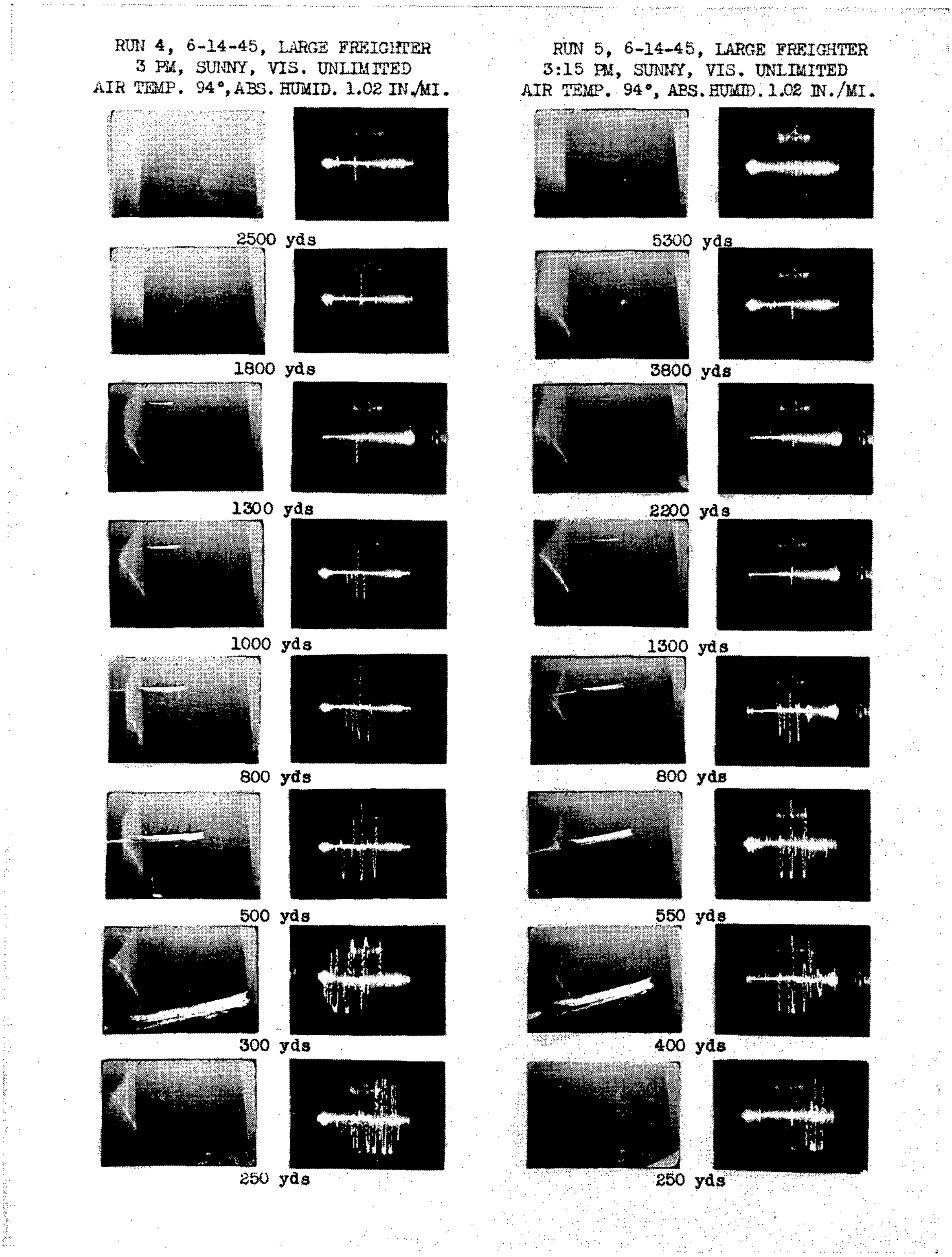


FIGURE 29. Typical record showing performance of Type L.

observations of ship traffic at the entrance to Delaware Bay were made for a period of three days, June 26 to 29, 1945. Watches until midnight on two evenings disclosed a complete dearth of ship traffic, only a small patrol boat being sighted. A lightship 3½ miles offshore, counted on as a standard night and day target, proved barely detectable under the very high conditions of absolute humidity which prevailed.

Fortunately, the trip to Henlopen was not futile, since an opportunity was provided for verifying the long suspected existence of a fading effect in the transmission of infrared radiation. First noticed in shore tests at Ft. Wadsworth, Staten Island, N. Y., and believed to have been observed in many flight approaches (since changes in altitude of the plane did not seem to explain signal variations), the effect was most pronounced during a portion of these tests. Photographs of CRO presentations of target indications, Figure 29, demonstrate the fading, within the time interval of a single scan (⅓ second), of near full-scale signals to nothing. It is, of course, understood that threshold suppression was employed in the presentation since little noise pattern is apparent. Hence, the "nothing" signifies the decrease of a signal from far above the existing noise level to a magnitude within the noise range.

Cause of the fading was attributed after the Ft. Wadsworth tests to either the cooling of the target by varying air currents or the passage between target and detector of air masses of varying moisture content. The latter now appears to be the true explanation. At the time of taking these photographs, the absolute humidity was very high, being equal to about 1.1 inches of precipitable water vapor per mile, the target was between 1 and 2 miles distant (a freighter), and a brisk but variable breeze was blowing. On other occasions, with equal moisture in the air, but without the breeze, fading was not observed, nor was it observed in the presence of wind when the absolute humidity dropped to the order of 0.7 inch per mile. Hence, there seems to be a complete circumstantial indication of the cause.

Fading must, therefore, be considered as one of the obstacles to infrared detection of targets. However, though annoying, it has not appeared to result in the sacrifice of much range of detection. With a high-persistence screen in the CRO, a continuity of signal indication is maintained during the scans in which signals are absent. In a robot device, a clamp circuit could achieve the same memory function, maintaining a missile on course continuously.

Actual measurements on the sensitivity were made as described in Section 9.7.4. The minimum detectable radiation density was found to be about 10^{-9} watt per square centimeter.

9.8

AN ASSESSMENT OF A FAR INFRARED BOMBSIGHT WITH ANGULAR RATE RELEASE

9.8.1 Introduction

The *far infrared bombsight with angular rate release* [FIRBARR] [15] is a combination of the *British angular rate bombsight* [BARB] and equipment to scan and establish a line of sight to any heat target by using the infrared radiation from the target. A 5- to 10-C differential between the target and background is enough to allow detection with this device at a distance of 1 mile. The United States' version of the BARB has been coded by the Navy as the MK23 bombsight.

The BTL under Contract OEMsr-636 undertook a preliminary study which included:

1. A mathematical analysis to obtain a first approximation to the bombing accuracy of FIRBARR.
2. The design and construction of the infrared equipment, including scanning system, thermistor bolometer, amplifier, and indicator.
3. The construction of test equipment and the procurement of tracking error data on simulated MK23 and FIRBARR bombsights.
4. An analysis of these tracking data to determine the optimum smoothing time of the MK23 release circuit in order to obtain minimum horizontal release errors with FIRBARR.

The tentative design objective for FIRBARR was that the probable error in horizontal release range should be less than 70 feet with manual tracking in an airplane in stable flight between 50 and 1,500 feet in altitude, and between 100 and 300 knots closing speed. The closing speed and the collision course were to be set up independent of this equipment.

9.8.2 Preliminary Mathematical Analysis

Based on a series of reports on "Low Altitude Bombing" prepared under Section 7.2 of NDRC, a

preliminary mathematical analysis was made which showed that in FIRBARR the tracking error must be less than 0.5 degrees in φ, the depression angle, in order to meet the design objective. For a manual MK23 bombsight having a probable error in φ of 0.1 degree and a smoothing time of 0.5 second the probable error in horizontal range is 30 feet at an altitude of 200 feet and closing speed of 150 knots.

THE INFRARED EQUIPMENT

The infrared equipment was designed to use the thermistor bolometer developed at Bell Telephone Laboratories under Contract OEMsr-636. The particular problem in FIRBARR was to design an amplifier, scanning system, and indicator which would allow the bombardier to track ships at sea to not more than 0.25 degree probable error in φ under low-level bombing conditions from ranges of 1 or 2 miles.

The amplifier and the input circuit connecting the thermistor bolometer to it were designed with the object of maximizing the resolving power and sensitivity of the system. A detailed discussion of the amplifier circuit design is given in Appendix A of the contractors' report.[15] A description of the physical construction and electrical characteristics is given in Appendix B of the same report.[15]

The collecting mirror in the scanning system is parabolic with the thermistor placed in the focal plane to permit a vertical scan of 6 degrees with a beam 3 degrees wide. Three separate mechanical systems were tried, but an offset rotating parabolic mirror mechanism was tentatively decided upon because of its simplicity and its potential ability to furnish the tilt and azimuth angles of the line of sight with a single mirror and amplifier.

Two different types of indicating systems were tried. The strobotron type is preferable to the oscilloscope for airborne equipment, since it is smaller, lighter in weight, and requires less electrical power to operate. It has the further advantage that it permits the identification of weaker infrared signals against the noise background by a ratio of at least 4 to 1.

Using a 3-inch diameter parabolic mirror having a 2-inch focal length, the offset rotating parabolic mirror scanning system, and the strobotron indicator, it is possible to track an infrared point target, the radiant energy density of which at the mirror surface is 5×10^{-10} watt per square centimeter. (This is total radiation without a filter.)

9.8.3 Test Equipment

In order to study the tracking errors in manually operated MK23 and FIRBARR bombsights, a servo-controlled "running rabbit" was built to provide either an optical or infrared line-of-sight equivalent to that from an airplane pursuing a collision course at constant altitude and airspeed over a ship at sea. This testing equipment provides a continuous photographic record (16-millimeter Fairchild motion-picture gun camera) of the tracking errors during the bombing run as well as a record (stylus on waxed paper) of the depression angle at release, both of which are accurate to better than 0.05 degree. In accordance with appropriate dial settings the servo automatically provides the line of sight during the 10 seconds prior to release for altitudes between 50 and 1,500 feet and closing speeds between 80 and 350 knots.

9.8.4 Analysis of Tracking Errors

Using the test equipment described above, a number of tracking error records were made during simulated bombing runs with a FIRBARR (mounted on a firm platform), including an oscillating scanning mirror and an oscilloscope indicator. Assuming an error of 25 feet in the determination of the altitude of the plane and 0.5-second exponential smoothing time in the BARB release mechanism, a probable horizontal release error of 50 feet is obtained. By increasing the smoothing time to 1.5 seconds, the probable horizontal release error is reduced to 32 feet. Since the theoretical improvement resulting from a further increase in the time constant is small and the equipment arrangement becomes difficult, 1.5 seconds has been chosen as the optimum smoothing time for the BARB sight with infrared scanning.

9.8.5 Present Status

The results of this investigation were sufficiently promising to warrant further development under Navy (Bureau of Ordnance) contract. The design objective is a bombsight incorporating infrared scanning and manual tracking which, when oper-

ated in an airplane in stable flight between 50 and 500 feet altitude at 100 to 250 knots ground speed, will have a probable error in horizontal release range of 50 feet or less.

9.9 THE PORTABLE SHIP DETECTOR [PSD]

9.9.1 Introduction

The pressing need for a device that could be used on the deck of a submarine without revealing its presence to detect an enemy craft at night and to determine its bearing led the Navy to request, as Project Control NS-121, the development of a portable infrared receiver for this purpose. The limitation to location on the deck of a submarine was later lifted by the Services. In addition the project was expanded as Project Control N-108 to include the detection of night landing parties, including (1) enemy transports or other large vessels at considerable distances, (2) landing barges and similar size vessels at 1- or 2-mile ranges, (3) small boats without engines carrying a few men at ranges up to a mile or more, by the infrared radiation emitted by them. It was desired by the Services that the equipment developed should be simple and easy to manufacture and operate.

9.9.2 General Description

The *portable ship detector* [PSD] [16] operates solely from the difference between the amount of heat received from the target and that received from an equal adjacent solid angle of background. The device contains two heat-sensitive thermistor detecting strips which are mounted in the focal plane of a Schmidt optical system. A motor oscillates the optical system through a small angle so that the image of the target falls alternately on the two thermistor strips. The small temperature changes which occur in the bolometer strips when a heat source enters the field of view are detected electrically and when amplified manifest themselves as audible or visual signals occurring at the scanning frequency. The signals yield "right and left" information so that the PSD may be adapted to automatic following.

As developed, the telescope unit, containing the optical system and the preamplifier, could be hand-pointed or supported by a pivot mounting on a tripod. The minimum detectable power density incident on the optical system was determined to be 3.6×10^{-10} watt per square centimeter. The complete equipment is shown in Figure 30.

9.9.3 Description of Component Parts

Optical System

Except for an external window, the entire infrared optical system is housed in a metal cell which is about 2.5 inches in diameter and 3 inches long. The radiation receivers are mounted in the focal plane of a Schmidt optical system which consists of a spherical mirror and a rock-salt correcting plate, the latter serving also as the cell window. The aperture of the system is 34 millimeters and the focal length is 22 millimeters; thus the speed is about $f/0.65$. The radiation detectors are about 0.2x1.0 millimeter and the space between them is approximately equal to the width of one of the detectors. Schmidt correcting plates, which have sufficient accuracy so that the circle of confusion is small when compared to the width of the detector strip, may be turned on a lathe.

The PSD thus has two fields of view which are rectangular corresponding to the images formed in the two detecting elements by a target. The field of view has been kept as small as possible for two reasons, namely, the minimum detectable signal, which is a function of the noise in the receiver, varies approximately with the square root of the area of the detector, and the noise and spurious signals due to thermal background increase rapidly as the vertical field is increased. The ideal condition would be to have the size of the image the same as the size of the detector, but reduction in the size of the field of view increases the difficulty in locating a target or following a target once it has been found. A field of view which subtends a vertical angle of 2.5 degrees and a horizontal angle of 0.5 degree was finally adopted.

Scanning System

The optical system, the preamplifier and the bolometer bridge are housed together in a small aluminum box which is roughly thermostated at a temperature above the highest expected ambient temperature. The aluminum box has a rock-salt window and forms what is known as the telescope

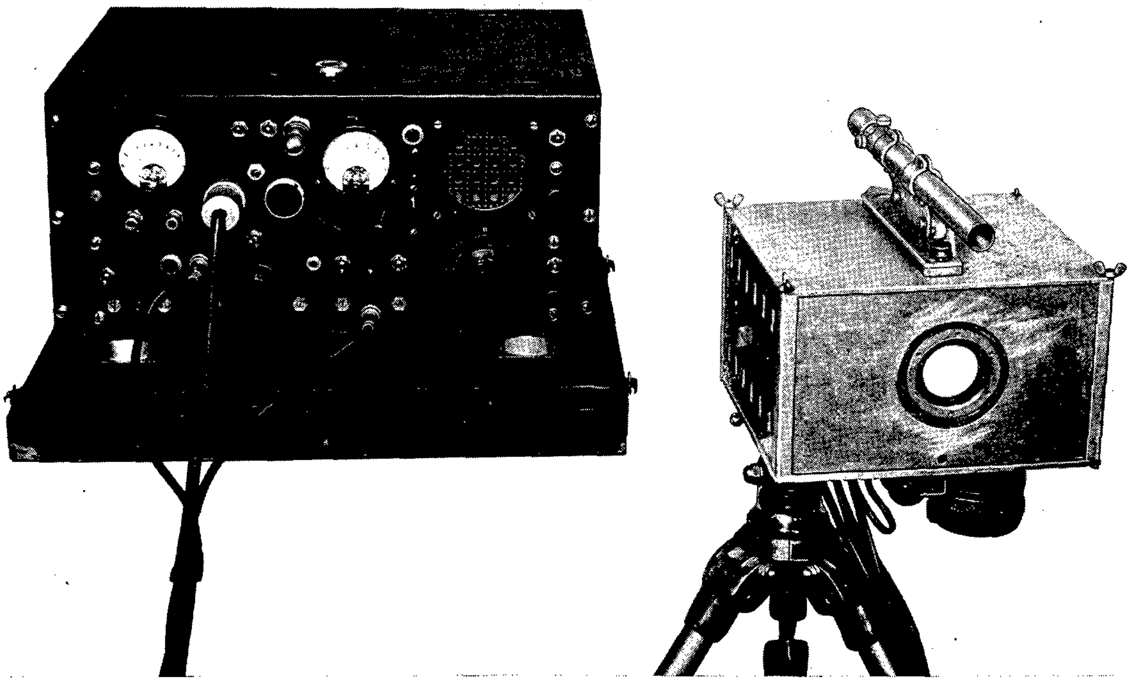


FIGURE 30. Photograph of portable ship detector.

unit. This box is mounted on pivots and the small angle of scan of the optical system is obtained by means of a cam driven by a small synchronous motor.

The scanning rate was chosen to yield an optimum performance, i.e., it must be slow enough to give the desired sensitivity yet fast enough to maintain a satisfactory flow of information. The characteristics of the thermistor elements adapt themselves well to a rate of oscillation of from 2 to 4 c. A rate of oscillation of the optical system of 2 c was finally adopted and at this rate four signals per second occur when a target occurs in the center of the field.

DETECTING ELEMENT AND AMPLIFIER

Detecting Element. The PSD employs an air-cooled thermistor bolometer, as described in Chapter 8, as its detecting element.

At the scanning rate adopted for the PSD, using detecting strips equivalent to a horizontal field of view of 0.5 degree and separated by a distance equivalent to 0.5 degree, the exposure time is about ⅙ second.

A reasonable match was realized by selecting thermistor strips which had a time constant of 120 milliseconds. The strips were then about 16 μ thick and were operated in air at a pressure of about 7 millimeters (Hg). At this pressure no gas-microphonic difficulties were encountered.

It should be recalled from Chapter 8 that electrically the thermistor bolometer is a high-resistance circuit element which has a large negative temperature coefficient of resistance. A receiver which is 0.2 millimeter wide and 1.0 millimeter long has a cold resistance of about one megohm. Because of the negative temperature coefficient of the material, there is a certain maximum voltage which may be maintained across the unit with a corresponding current. For greater current in a unit, a ballast resistor must be used. For the receiver described previously, the peak voltage is about 35.5 volts. It was found experimentally that for the PSD equipment the best signal-to-noise ratio was ordinarily obtained when the voltage across the bolometer was about 20 volts.

Bolometer Bridge and Amplifier. The thermistor bolometers are made with two arms and two wire-wound resistors, the remaining two arms of a Wheatstone bridge across which is applied an alternation potential of 1,000 c from a specially shielded oscillator. Means are provided for estab-

lishing resistive and capacitive balances. The output of the bridge is led directly into the preamplifier which consists of a single pentode stage with a cathode follower. This network feeds into a low-impedance line.

The signal from the preamplifier passes through a detecting unit which produces a rectified envelope of the signal, modulated by the variation in the resistive balance of the bolometer bridge. The final amplifier is a narrow passband amplifier of frequency width 2 c, built from simple RC filters, and has an overall gain of about 3×10^6.

Power Supply

The power supply is a conventional regulated unit of the degenerative type. There is some forward-acting compensation against line voltage changes. It operates satisfactorily on line voltages from 105 to 125 volts. More recently a power supply has been designed for use with the *stabilized ship detector* [SSD] (see Section 9.10) which is superior to the one described here.

Presentation Unit

In order to provide quantitative measurement of the signal strength, a zero-center milliammeter is used to indicate the difference between the plate currents of the two output tubes. A signal may be observed visually by blinking lights which are operated by relays in the plate circuits of the output tubes. The output stage is, in addition, used to operate a dual "magic eye." The relays also control the output of oscillators which have frequencies in the audible ranges so that the signal may be detected by the use of headphones. The output of the amplifiers also operates relays which give "right" and "left" indications.

It is desirable to eliminate those signals which occur when the heat image is scanning only across one strip (off-center scanning). The phase angle of the low-frequency output signal relative to the mechanical phase angle of the telescope or scanner depends not only upon the amplifier characteristics but also upon the position of the heat image as it scans across the strips. When the telescope is pointed so that the heat image falls periodically on only one bolometer strip the output signal differs in phase by 180 degrees from the case when the heat image falls alternately on the two strips. It is obviously desirable to be able to distinguish between the on-center signal and the right and left off-center signals. The on-center signal has approximately twice the amplitude of the others, but in detecting a target of unknown strength either a comparison of two signals strengths would have to be made or the three signals would have to be located and the center one chosen. The 180-degree change in phase angle makes it possible to pick the center signal easily and unambiguously and incidentally to increase the discrimination against unwanted signals.

A mechanical switch operated by a cam which is driven by the scanning motor is used to short to ground alternately the two sides of the balanced low-frequency amplifier. This scheme has been called a "beep-canceler," since it removes unwanted audio signals.

In the case of night detection of naval targets, the target is warmer than the background during all seasons. The beep-canceler sets the condition that the relays may operate only when the image of a hot target is scanned on-center. Hence the relays operate alternately, giving the high and low pitch sounds, and open the magic-eye shadows. For off-center scanning the negative pulses do not operate the relays, so no audible signal is given, but the magic-eye shadows close alternately, indicating that there is a target a degree or two off center.

The thermal background may have hot or cold spots. The beep-canceler, of course, can do nothing to distinguish between a target and a hot spot in the thermal background. Off-center scanning of a cold spot will produce relay signals, while on-center scanning will not cause relay operation; for the on-center case, the negative signals will appear on the magic eye.

In some instances it was desirable to use a recording output meter; in this case the beep-canceler was used as a synchronous rectifier.

9.9.4 Range and Sensitivity

Minimum Detectable Signal

For field operation, the limitation on the sensitivity is generally fixed by the thermal background conditions. To test the sensitivity of the device working against a perfect background, i.e., to determine the limit of sensitivity due to circuit noise, the following method was employed. A black-body source which is about 10 to 25 C above room temperature and subtending about 7 minutes[2] is used

and the minimum gain of the amplifier is found for which relay operation is reliable. A cover is then placed over the cell and with the same scanning motion the gain of the amplifier is increased until 20 to 30 false relay operations occur per minute. Since 240 relay operations occur per minute (scanning rate 2 c) when the source is reliably detected, the signal-to-noise ratio might be said to be about 8 to 1. The flux incident on the apparatus is then computed and from the ratio of amplifier gain settings the minimum detectable signal may be obtained. In a typical trial the minimum detectable signal for a signal-to-noise ratio of 8 to 1 was found to be 3.6×10^{-10} watt per square centimeter. When the scanning speed was reduced to 1 c and lower resistance units were used which could be operated at a higher fraction of their peak voltage, the minimum detectable signal for the same signal-to-noise ratio was 10^{-10} watt per square centimeter.

In making these measurements it is ordinarily convenient to use a somewhat larger source and correspondingly lower gain, since temperature gradients in the screen which forms the background are troublesome. A correction may be readily made by scanning the background without the source and noting the amplitude and phase of the signal.

Detection Ranges

The PSD was first demonstrated to Section 16.4 on May 11, 1943. In spite of rain and fog the destroyer *Semmes* with only two forestacks active was reliably detected at 4,100 yards. Subsequent tests on June 18, 1943, after further improvements had been made on the sensitivity, showed ranges of 6,500 yards on ship traffic near Solomon's Island, Maryland.

The data presented in the following paragraphs were obtained during tests which were arranged by the Bureau of Ships. All ranges which are given are based on radar information; the aspect of the vessel was obtained from plots of the courses of the target vessel.

1. These tests were made with the PSD and another far infrared detector mounted on top of the periscope of the USS *Bass* to determine the range and the bearing of the USS *Melville* and DE 177. The tests were carried out on December 1, 1943, from 19:40 to 23:40 with the submarine at periscope depth, a position sufficiently stable for the successful operation of the unstabilized PSD. The PSD was able to determine the target bearing within 0.5 degree. The results are stated in Table 4.

Table 4. Results of tests made on target ships.

Target	Aspect bow-on (degrees)	Range (yd)
USS *Melville* (4,000 tons)		5,700
	30	5,500
	145	5,300
DE 177		4,450
	335	3,900
	145	6,200

The ranges noted are not necessarily threshold ranges, since only a small fraction of the available amplifier gain could be used because of poor thermal background. Because the two detectors which were in operation did not "look" in the same direction, the periscope was trained alternately by the two operators. During the tests, the PSD ceased to function because of salt water in the auxiliary unit which was inside the conning tower.

On December 2 the PSD was in operating condition for a continuation of the tests, which had to be abandoned because of a collision with the *Melville* during the first run. Strong signals preceded the collision.

Table 5. Tests at the Bureau of Ships Test Station, Cape Henlopen, Delaware, February 23 to 24, 1944.

Target	Aspect (degrees)	Range (yards)	Time
LCI	90	6,500	19:40–04:30
	10	6,000	19:40–04:30
	90	7,800	19:40–04:30
	0	3,900	19:40–04:30
LCT	170	5,600	19:40–04:30
	5	5,800	19:40–04:30
	9	8,600	19:40–04:30
Tanker	Stern	11,000	19:40–04:30
Cargo ship	Stern	9,000	19:40–04:30
LCI	30	7,000	20:50–01:10
	5	5,320	20:50–01:10
LCT	210	5,000	20:50–01:10

2. The same model of the PSD was land-based at an elevation of about 50 feet above sea level at Cape Henlopen for tests from February 21 to 24, 1944. Data taken during these days on a tanker, a cargo vessel, an LCI, and an LCT are given in Table 5.

9.9.5 Present Status

Since the tests with the PSD showed that a nonstabilized receiver, with the requisite small angle of view for necessary sensitivity of detection of ship targets at desired ranges, could not be used satisfactorily for search purposes from a ship's deck, this development as such was terminated. The results of this work were used, however, in the development of the SSD.

9.10 THE STABILIZED SHIP DETECTOR [SSD]

9.10.1 Introduction

Shipboard experience with the portable ship detector [PSD] (see Section 9.9) showed that satisfactory rapid search for unknown targets with far infrared receivers was impracticable without the following improvements: (1) stabilization of the receivers; (2) elimination of manual pointing; (3) provision for a "target bearing memory." The Bureau of Ships therefore requested, under Project Control No. NS-181, that a gyrostabilized, automatically scanning and recording thermal receiver incorporating the general features of the PSD, be developed for the detection of ships in darkness, smoke, or light haze conditions. The military characteristics desired were that the detecting element be mounted in a Schmidt optical system which would scan automatically at a fixed rate through a horizontal angle of 300 degrees; that the scanning head be mounted on a gyrostabilized platform to be furnished by the Navy; that the signal be amplified by a band-pass amplifier, the passband being chosen to take advantage of the fixed rate of scanning, and that the received signal be recorded by a suitable recorder.

The signal-to-noise ratio obtainable with the PSD, which employed automatic scanning over a small horizontal angle and manual pointing for search purposes, was high, since with a scanning rate of 2 c a band-pass of two octaves is only a few cycles wide. The minimum detectable radiant power density for the PSD was about 4×10^{-10} watt per square centimeter incident on the 34-millimeter diameter mirror for a 2-c scanning frequency (four signals per second). The problem in the development of the *stabilized ship detector* [SSD] [17] was to devise a receiver having sensitivity comparable to, or greater than, that of the PSD together with the additional desirable operational characteristics.

The equipment as developed possessed this desired sensitivity as well as the desired operational features of furnishing relatively rapid search for good bearing accuracy and resolution of targets. A permanent record is made of all targets detected within the area scanned.

9.10.2 General Description

The complete SSD equipment consists of five units: (1) a scanning head, containing the two-strip thermistor bolometer mounted in the focal plane of a Schmidt optical system, and the preamplifier, which is mounted on a stabilized platform on the deck or superstructure of the ship and which may be adjusted to rotate through an angle of 360 degrees or a smaller angle in the horizontal plane at constant angular velocity with reference to fixed axes; (2) a synchro-driven yaw-correction unit to correct the motion of the scanning head for the yawing of the ship and consequently to produce a scan relative to fixed axes rather than relative to the ship and to permit a record to be made of the true bearing of the target; (3) an amplifier of special characteristics for the bolometer output; (4) a signal recorder; and (5) a regulated power supply operating directly from the ship's power lines. Units (2) to (5) may be located in the CIC room of the ship for convenience of operation and more rapid receipt of intelligence.

The heat image of any target within the angle which is scanned falls successively on the two thermistor strips. The extremely small temperature changes of the heat-sensitive elements are detected electrically, giving rise to two electrical pulses of opposite polarity. The complex output pulse from the amplifier actuates an electrically operated recorder which is operated in synchronism with the scanning head and which prints on a paper chart a continuous, permanent record. In the case of sector scanning the stylus moves back and forth across the recording paper, which is driven slowly. The position of the stylus at any instant corresponds to a certain true bearing of the scanning head. Chemical recording paper is used and the passage of an electric pulse produces a discoloration of the paper. If the true bearing of a target remains constant for successive scans, the record consists of a series of

spots which lie in a straight line parallel to the motion of the paper chart. The constant motion of the paper establishes a time scale, hence the record produced is one which gives bearing as a function of time.

9.10.3 Description of the Component Parts

Optical System

Except for an external, coated silver-chloride window, the entire infrared optical system is housed in a sealed metal tube which has a rock-salt window. The heat sensitive detectors are mounted in the focal plane of a Schmidt optical system which consists of a spherical mirror and a rock-salt correcting plate which also serves as the cell window. This complete unit is designated as the "cell" and, in the latest model, has an aperture of 150 millimeters, which is near the maximum aperture practical with rock-salt optics at the present time. The cell units are brought into focus by placing shims between the bolometer housing and the fixture on the post supporting the bolometer. When the position for best focus has been determined, the cell is evacuated, filled with dry air at a pressure of about 1 centimeter (Hg) and sealed off.

It is important that the optical system have the maximum sensitivity for its weight and volume. The Schmidt optical system has therefore been chosen in preference to the parabolic mirror system, inasmuch as it is possible to demonstrate [18] that for equally good definition the former system may occupy only about ⅛ the volume of the latter system. The optical system of a carefully constructed SSD cell of 150 millimeters aperture has a circle of confusion of about 6 minutes of arc.

The SSD has two fields of view corresponding to the two parallel thermistor bolometer strips each of which is 1.0 millimeter long and 0.2 millimeter wide. The strips are 0.2 millimeter apart. These strips, placed vertically at the principal focus of the optical system with an 83-millimeter focal length, produce two fields of view each 40 minutes high and 8 minutes wide, separated by 8 minutes.

It is desirable to keep the vertical extent of the field of view small in order that spurious signals be kept at a minimum. It is fairly obvious that the ideal condition would be that the size of the image of the target be comparable to the dimensions of the detector or bolometer strip. This condition may be approached for land-based operation but cannot be realized at sea because of stabilization difficulties. A naval target, such as a destroyer escort at 10,000 yards, subtends a vertical angle of less than four minutes, whereas stabilization errors may be of the order of ± 10 minutes.

There are several factors which must be considered in choosing the vertical extent of the field of view. Some of these which relate to the stabilization problem are: the random errors in the gyro-vertical; possible drifts in the mean vertical (as occur during rapid changes of course); ship flexure between the gyro-vertical and the scanning head (particularly for mast mounting); and inaccuracies in alignment which occur during installation or maintenance. Particularly in the case of mast mounting, small craft such as PT boats may escape detection if the vertical field is too small. Consideration of these factors led to the choice of a vertical field of view of about 40 minutes. It might be well to increase this to about one degree for masthead operation.

The considerations leading to the choice of the width of the field of view and the separation of the fields of view are more complex than in the case of the extent of the vertical field of view. Factors to be considered are: desired resolution, sensitivity, background noise, and the shape and duration of the output pulse. The fields of view which have been used in the SSD give reasonably good resolution; ordinarily, targets whose bearings differ by one degree or somewhat less may be resolved. Increasing the horizontal fields of view would obviously decrease the resolving power of the detector.

It is desirable that the extent of the entire heat image of a small target (including the circle of confusion) be comparable to the strip width. The optical system of a carefully constructed SSD cell of 100-millimeter aperture has a circle of confusion of roughly four minutes; therefore, the heat from a small target, such as a destroyer escort with stern aspect of 10,000 yards, is concentrated successively on the strips.

Scanning Mechanism

The optical unit and the d-c preamplifier are mounted together on an aluminum plate which is oscillated at a rate of 6, 12, or 18 degrees per second as desired, by a synchro motor through a gear train. The scanning mechanism provides either for unattended 360-degree search or, by a rapid adjustment,

for scanning over smaller section angles of 25, 50, or 150 degrees. Because the SSD is to be operated on shipboard it is necessary that the scanning be with reference to fixed axes rather than relative to the ship, since the yawing of the ship causes poor alignment of the signals on the record.

A record of the true bearing of a target was obtained by putting gyrocompass corrections into the motion of the scanning head. The drive unit to accomplish this contains a motor, two synchro generators and a Ford Instrument Company compass follow-up mechanism. One synchro generator was driven directly by the motor at a constant speed and was linked electrically to a synchro motor in the recorder to provide power for the stylus. At the end of each scan two phosphor-bronze fingers attached to the stylus carriage closed contacts in a relay circuit which controlled the direction of rotation of the driving motor. The other motor, which was linked electrically to a synchro motor in the scanning head, was driven by a gear train in which the gyrocompass corrections were mixed with the scanning drive by means of a mechanical differential.

Three dials were provided from which could be read the ship's course and the train of the scanning head in terms of relative and true bearing. By means of a screw-driver adjustment of a differential, the position of the head might be changed to correspond to the true bearing indicated on the recorder.

In Figure 31 is shown the complete equipment for the synchro driven system designed for operation from the ship's power lines. The electronic units are the final amplifier (right) and the power supply for the bolometer and preamplifier.

Detecting Element and Amplifiers

Detecting Element. The SSD employs gas-cooled thermistor bolometers for the detection of the infrared radiation. The thermistor strips are mounted on a molded glass blank which is held by a polystyrene cup covered by a thin plane rock-salt window. A well is molded in the glass disk very nearly 1 millimeter wide and about 0.25 millimeter deep and the electrical contacts are made quite near the edges of this well. A small breather hole is provided so that the optical unit may be exhausted without damaging the detector units. The heat-sensitive areas are rectangular, 1.0x0.2 millimeter, and are separated by 0.2 millimeter.

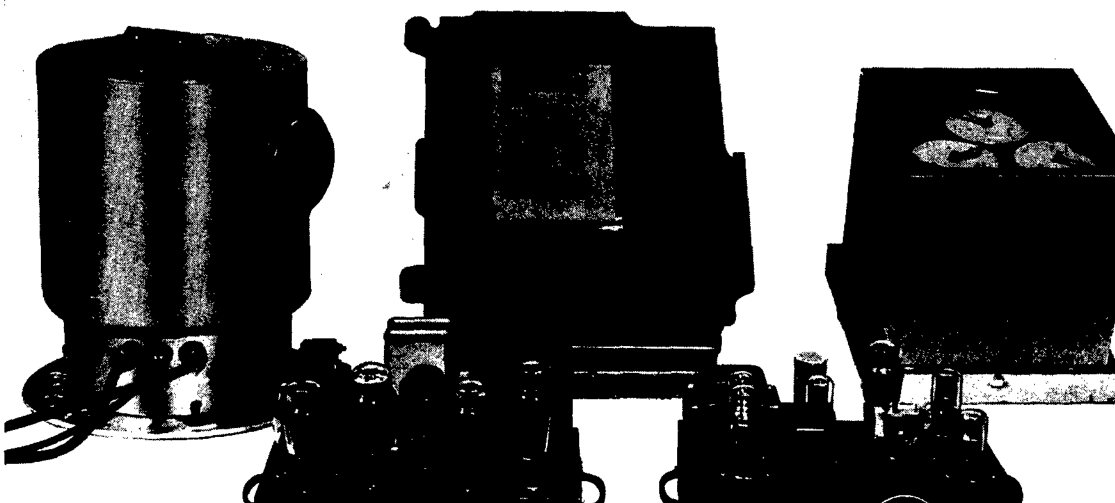


Figure 31. Photograph of stabilized ship detector.

Electrically, each strip is a high-resistance circuit element with a large negative temperature coefficient of resistance, the resistance of a single strip at room temperature being about 10 megohms. A constant potential difference is maintained across the two units connected in series and the variation of potential across one of the units gives an indication of temperature changes which occur in either unit. Under operating conditions the electric power dissipation in the units raises their temperature about 15 centigrade degrees above the surroundings and the resistance of each unit decreases to about 7 megohms. A certain maximum voltage exists which may safely be applied to the thermistor bolometer (see Chapter 8). For practical operation the maximum sensitivity of the bolometer to radiation lies at somewhat less than peak voltage. The SSD cells were operated at about 80 per cent of peak voltage.

The present thermistor bolometers show little evidence of increase in noise with increase in current through the units. Because of the decrease in resistance which occurs with increasing current in the units the "Johnson noise" should decrease with increasing current. Most thermistor bolometers show an actual decrease in noise as the current is increased. The condition has been set arbitrarily that a unit is satisfactory if the noise at 80 per cent of peak voltage is no greater than the noise without current.

In the initial design of the SSD the shortest detectors which were practical to manufacture at the time were chosen. The desired vertical field of view and the length of the detectors set the focal length of the mirror. The width of the detector (0.2 millimeter) was chosen to give sufficiently good resolution and a reasonably short electrical output pulse for 6 degrees per second scanning. The first cells, which were of 64-millimeter aperture, formed images which were sharp enough to allow the use of the narrow detectors. Later, cells of 100-millimeter aperture (of the same focal length) were developed; these also had sufficiently good optics to perform efficiently. The most recent cells, of 150-millimeter aperture (f/0.57), are not entirely satisfactory because of excessive chromatic aberration.

Amplifier. The electronic units of the SSD consist of the preamplifier, a power supply for the bolometer and a final amplifier.

Preamplifier. The preamplifier is the most critical part of the electronic equipment. No satisfactory solution of the problem of isolating the preamplifier from ships' vibrations has been found. Currently available methods could not be used to isolate the optical unit from vibration because of the necessity for maintaining the axis of the optical unit on the horizon. The entire equipment was therefore subjected to the ship's vibration, but all parts were very rigidly mounted in order to avoid amplification of the vibrations. The preamplifier should operate satisfactorily on signals which are a little more than 1 μv. It is desirable to use as few tubes as possible but to have sufficient gain that the output signal be large compared to any noise due to slip rings or hum pickup in the output cable. The preamplifier has a voltage gain of about 8,000 which is sufficient to provide about 10 mv with minimum signal input.

Whether the noise limitation is set by the microphonics in the input tube or by the Johnson noise of the input circuit, the best signal-to-noise ratio is obtained if the input impedance of the amplifier is large as compared to the resistance of the thermistors. A high-input impedance was obtained by the use of a 100-megohm grid resistor and the largest possible cathode resistor in keeping with the gain requirement. The large cathode resistor provides sufficient bias to prevent the lowering of the input impedance due to grid current.

Since high impedances are involved, it is necessary that all wires and components of the input circuit be very rigid and well insulated. The input impedance at the coupling unit is about 30 megohms.

The frequency response of the preamplifier is 3 db down at 1,000 and 2,000 c. In the investigation of the pulse distortion produced by the final amplifier it was convenient to work with a fairly wide-band amplifier. It would probably be desirable to narrow the bandwidth of the preamplifier and use a cathode-follower output circuit to match the line.

Power Supply Unit. The voltage-regulated power supply for the preamplifier consists of a high-voltage regulator of the conventional degenerative type incorporating a pentode amplifier, and a filament supply which is regulated by three 6L6 tubes. For the filament supply the voltage fluctuations are applied to the screens of the 6L6's in such a manner as to oppose any change in the output voltage. The potentiometer to which the screen of a 12SJ7 is connected controls the amount of a-c applied to the screen for compensation and also varies the d-c

screen bias. The output voltage is adjusted by means of the potentiometer which determines the potential of the control grid.

Final Amplifier. The function of the final amplifier is to provide sufficient power for writing on electrolytic recording paper and also to present the electrical pulse in such a manner as to give the most intelligible record. The matter of providing sufficient power is straightforward while that of presenting the pulse to best advantage is far from simple. Considerable work, both experimental and theoretical, has been done to determine the optimum passband and phase shift of the final amplifier. The bolometer arrangement is such that a heat image which sweeps across the two bolometer strips produces two electric pulses of opposite polarity. After the pulse passes through the preamplifier, the shape approximates a single sine wave, with duration approximately equal to the time for the heat image to traverse the bolometer strips.

In order that such a pulse pass through an amplifier without distortion, theoretically the passband should extend from a frequency of zero to infinity. The amount of energy in any frequency interval may be computed, and for the SSD pulse, at a scanning rate of 6 degrees per second, the maximum energy lies near 9 c and a passband extending from 0 to about 20 c would pass most of the energy. An amplifier with a large number of bandwidths was used to determine the band for which the signal-to-noise ratio was most favorable. A passband from 6 to 25 c appears to be as satisfactory as any.

Because of the phase-shift and frequency response characteristics of the amplifier, the pulse is distorted in its passage through the amplifier. The best results in the field have been obtained with an output pulse which has one strong pulse in one direction and a reversed pulse on each side. The central peak is printed on the paper and the two smaller peaks, which are of opposite polarity, cancel random noise pulses which may occur. If the spaces between the traces made on successive scans are small enough so that the adjacent traces almost merge, the black signal indication has a white border on each side (Figure 33).

In sector scanning the polarity of the pulse from the bolometer is different in the two directions of scan. The inversion is accomplished by a phase inverter tube in the final amplifier. A relay which is operated by contacts in the recorder switches from one side of the inverter to the other when the direction of motion of the scanning head is reversed.

The total gain of the amplifier is about 3,500. A calibrated attenuator permits gain adjustment in steps of 3 db, from 0 to 40 db. The switch on the input changes the gain by 40 db. Such an extreme range is not necessary in the field but is convenient for laboratory measurements.

Representation Unit

The SSD recorder was a rebuilt British AS/3-type chemical recorder designed for underwater sound work. A Pt-Ir stylus is used as the marking electrode and moves across the paper at a constant rate. The recording paper, which is damp, is fed from an airtight humidor and passes over a Monel roller which acts as the second electrode. In the earlier tests Sangamo fluorescent recording paper was used. With this paper a positive voltage on the stylus produces a black mark; a negative voltage has no effect. The impedance of this paper is about 10,000 ohms and about 0.2 ma at 2 volts is required to produce a signal of medium intensity.

In the later work Fax recording paper was used. The best results have been obtained by using the same electrode materials as were used with the Sangamo paper; however, for this paper the stylus should be negative. The paper has the advantage of making a black-on-white record, whereas the Sangamo paper makes a black-on-pink record. The impedance of the Fax paper is about 800 ohms and about 15 ma at 12 volts are required.

The Fax recording paper has several disadvantages. The stylus wears quite rapidly and the roller must be cleaned after a few hours of operation. Air circulation within the recorder is critical; if the paper dries too quickly no marking is obtained and if it dries too slowly the record darkens almost immediately. The paper is easily contaminated and at present deteriorates while in storage.

9.10.4 Field Tests

Cape Henlopen Tests, February 21 to 24, 1944

The first official tests of the SSD equipment were conducted in cooperation with the Bureau of Ships at Fort Miles, near Lewes, Delaware, at night under rather favorable atmospheric conditions. The Surf Club, which served as headquarters, is located 50 to 100 yards from the sea. To the east and southeast

is open ocean; Cape May is about 12 miles northeast. All tests were run with targets against a sea horizon.

On the night of February 21, Model 1 SSD was mounted on the observation platform of the Surf Club, roughly 50 feet above the sea. The only chance targets which were ranged by radar were a tanker and a cargo vessel. The SSD record showed that the tanker was detected by the SSD to a maximum range of 14,100 yards. The cargo vessel *Admiral Byrd* was followed to about 14,700 yards.

For the tests of February 23 and 24, an LCT and an LCI were used as controlled targets for Model 2 SSD (64-millimeter diameter optics) mounted 35 feet above the sea.

The ranges at which targets may be detected depend considerably upon the aspect of the target vessel; hence for each test two ranges are given. By the minimum range (min R) is meant the closest approach of the target vessel without detection and would be expected to correspond to a bow or stern view (aspect 0 or 180 degrees) for the type of vessels used. The maximum ranges (max R) are simply the greatest distances at which the targets were actually detected. A summary of the range results in yards is given in Table 6.

TABLE 6. Range data for tests made February 23 and 24, 1944.

Date	Target	Min R	Aspect	Max R	Aspect
Feb. 23	LCI	9,200	10°	14,100	125°
Feb. 23	LCT	8,700	0°	10,500	150°
Feb. 24	LCI	10,600	25°	15,100	130°
Feb. 24	LCT	7,300	0°(?)	15,100	

These tests showed that the minimum range of approach without detection of an LCI (bow or stern view) was about 9,000 yards and of an LCT (bow or stern) about 7,300 yards. With more favorable ship aspects the LCI was reliably detected up to 15,000 yards and the LCT up to 10,500 yards. In one special test in which the LCI maneuvered without lights in a complex pattern it was continuously detected at all ranges within 14,000 yards, except for one brief period at 10,500 to 12,000 yards range with bow aspect.

A portion of the SSD record made on February 24 is reproduced in Figure 32. The trace of the LCI is marked with an X. The signal due to the lightship at 7,100 yards is indicated on the record. The bearing accuracy of the type of radar used for ranging was not sufficiently great to check the accuracy of the bearings read from the SSD record with a precision of 0.25 degree. Occasionally information from the SSD record assisted radar in selecting the proper target.

The radiation temperatures of various parts of the LCT and LCI were measured by means of a radiation pyrometer.[19] The only parts of the LCT which were warmer than the air (about 5 C) were the galley stovepipe, which was 8 inches by 5 feet, and the pipe on the bilge pump, which was not well exposed to horizontal view and was at 31 C. No conspicuous warm areas on the LCI could be found. It was concluded that the ship was a thermal target by virtue of its silhouette against the background.

The visibility was good on both February 23 and 24 although the first night was slightly clearer. The visibility was not estimated and the relative humidity was not determined.

Following those excellent tests, certain features requested by the Bureau of Ships were incorporated in the equipment better to adapt it for operational use. These included weatherproofing, ambient temperature compensation, a regulated power supply unit for the a-c preamplifier operated directly from the ship's power lines, and the determination of the best amplifier pass band for the detection of weak signals in a noise background.

Operational tests of the SSD aboard the USS *Marnell* on May 8, 1944, indicated that the above improvements had been satisfactorily accomplished but indicated the need for a reduction in microphonics, a correction for the yawing of the ship to permit the identification of a weak signal on the chart in a rough sea, and a reduction in the vibration of the stable table furnished by the Navy.

Work was undertaken to reduce the amplitude of vibration of the stable table. The microphonics, which were found to be caused essentially by the gas swish in the bolometer cell, were effectively eliminated by modifying the cell so that the bolometer was enclosed in a very small housing. An auxiliary unit for yaw correction was constructed. This unit contains means for adjusting the SSD recorder to give true bearing and indicates to the operator by means of three dials at all times the relative bearing of the scanning head, the true bearing, and the ship's course. In addition, the driving mechanism for the scanning head and the power

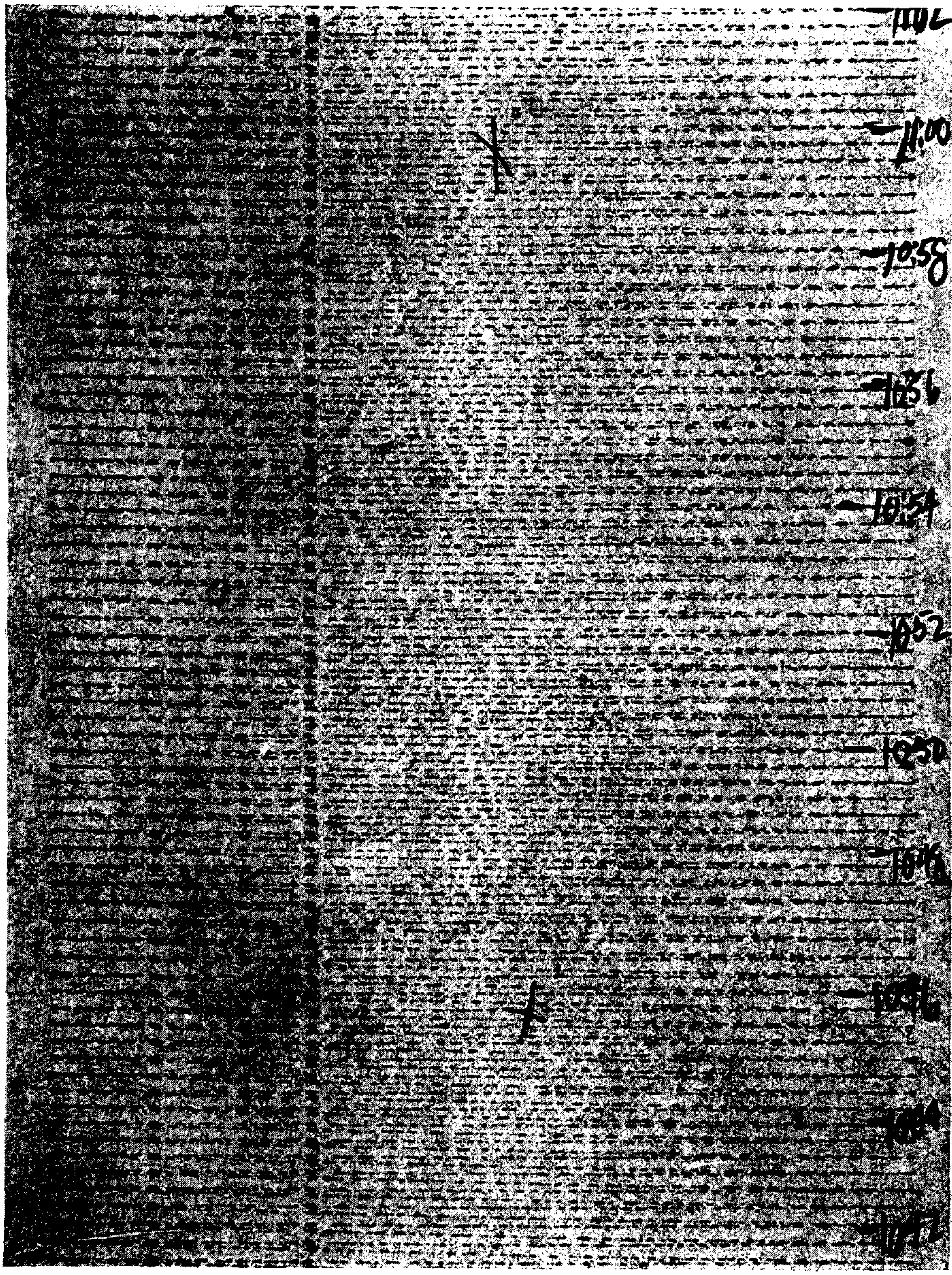


FIGURE 32. SSD record made at Cape Henlopen.

supplies for the final amplifier and for the bolometer were improved.

In tests on the *Marnell*, September 11 to 13, 1944, a tanker with stern aspect was detected up to a maximum range of 6,000 to 7,000 yards under the unfavorable atmospheric conditions of 77 F air temperature, 90 per cent relative humidity, and low visibility.

Marnell Tests,[20] October 23 to November 3, 1944

The SSD equipment was again placed on the *Marnell* at Cape May, New Jersey, on October 22, 1944, and remained on board until November 3. In the period between the departure from Cape May on October 23 and the arrival at New London, October 27, data were taken four nights outside New York Harbor; passing and harbor traffic provided chance targets. Tests on a controlled destroyer escort target were run in the New London area on October 30 and 31 and November 1, as a demonstration to Armed Services representatives.

Scanning heads were mounted on two stabilized tables which were located on the top deck of the *Marnell*. The height above the water was about 23 feet. The remainder of the equipment, which consisted of the recorder, amplifier, power supply, and mechanical driving unit, was set up in the experimental station on the deck below. Range information was obtained from the ship's type SF-1 radar.

The scanning motion of the head was at the rate of 6 degrees per second, and the full width of the record corresponded to a scanned sector of about 45 degrees. A bolometer cell having a 64-millimeter aperture was used in these tests.

If the chance targets, identified as freighters, Liberty ships, and merchants, are treated as a group the average definite signal range (defined as the distance at which the presence of a target is established under search conditions) is 9,950 yards. For these larger targets the maximum definite signal range was 18,000 yards, and the minimum 5,200 yards. Very nearly 75 per cent of the ranges were 9,000 yards or greater.

The section of record reproduced in Figure 33 was obtained between 04:15 and 06:00, October 24, when a convoy and escort vessels were encountered about 10 miles off Ambrose Lightship. This was the only SSD record obtained of a convoy at sea and indicates the resolution which is obtainable.

For the tests off New London, the *Breeman* (DE-104) served as the target.[c] Maneuvers were planned to give bow, bow-quarter, broadside, stern-quarter, and stern aspects of the target vessel. The results obtained on the three nights were reasonably consistent; the average definite signal ranges for the runs on the three nights were 6,850, 6,770, and 6,010 yards.

A summary of the data in terms of the aspect of the target vessel is given in Table 7, in which the tracking signal range is defined as the maximum distance at which the bearing can be obtained for a target, the presence of which has previously been verified.

Table 7. Target *Breeman*; October 30 to November 1, 1944.

Aspect	Runs	Definite Signal Range			Tracking Signal Range	
		Avg	Max	Min	Max	Min
Broadside	5	5,880	8,000	4,700	9,500	5,400
Stern	11	7,045	10,000	5,100	11,000	6,100
Stern quarter	6	7,350	10,800	5,000	11,200	5,500
Bow quarter	3	5,270	6,000	4,400	6,900	5,800
Bow	3	3,970	4,500	3,400	6,700	4,000
All aspects	28	6,380	....	....	....	....

Cape Henlopen Tests, March 20 to 24, 1945

In order to increase the receiver responsivity, bolometer cells 100 and 150 millimeters in diameter were developed and constructed in cooperation with the Bureau of Ships. The mounting for the gas-cooled thermistor bolometer was modified to reduce the volume of gas surrounding the bolometer and hence the microphonics due to gas swish. One of the SSD amplifiers was modified to provide the greater power required by Fax chemical recording paper, which was found to be superior to both the Sangamo fluorescent paper previously employed and to Teledeltos paper.

The SSD equipment previously field-tested was designed for sector scanning (50 degrees or less). In order to permit the visualized operational need for means of changing quickly from sector scanning to 360 degrees search or vice versa, a design was completed which permits unattended 360-degree search and which can be adjusted to permit either or both scanning heads to be converted quickly to

[c] Radiation temperature measurements of exposed surfaces of the target vessel and of the horizon background were made during the test at sea on October 31, 1944.[20a]

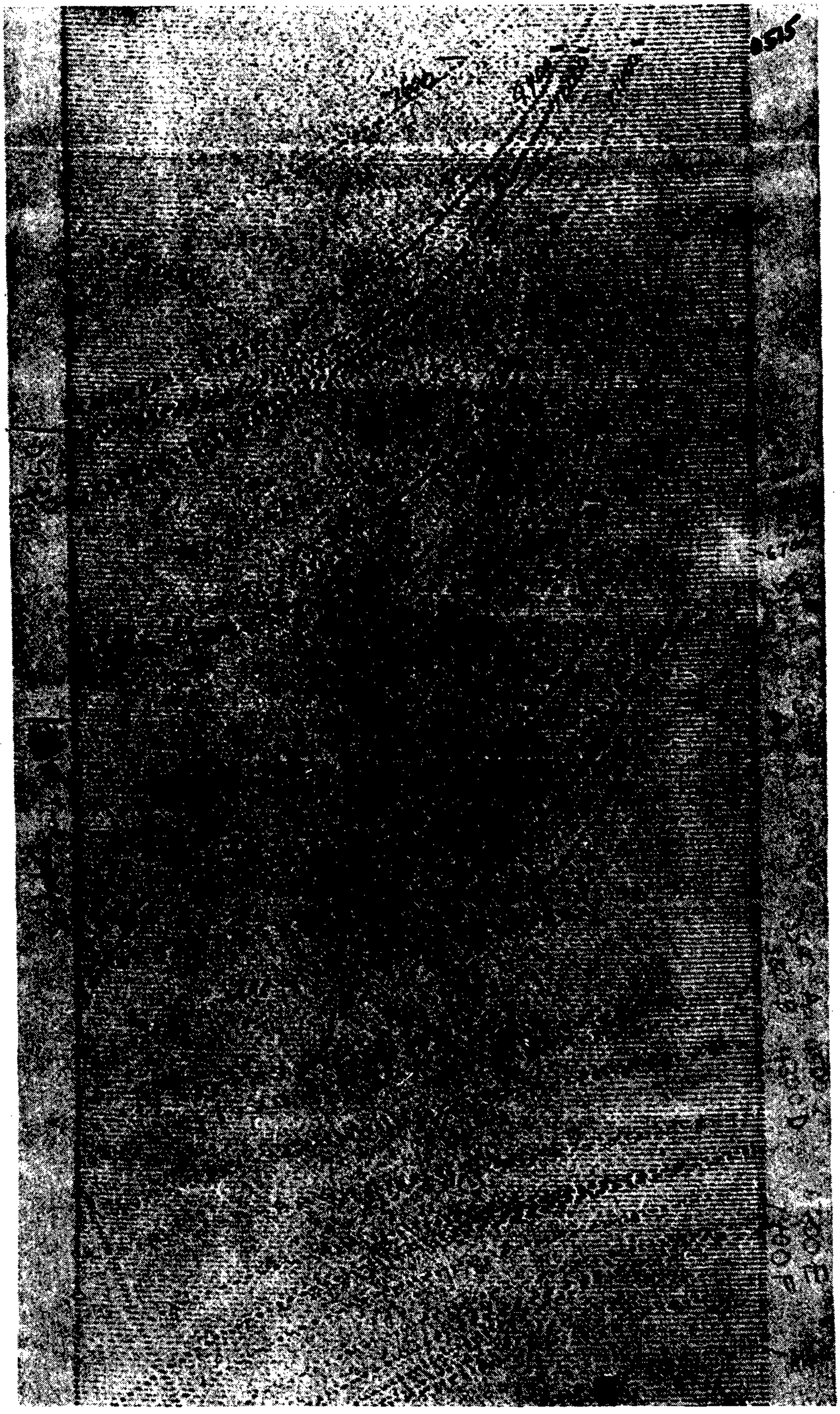


FIGURE 33. SSD record made of a convoy near Ambrose Lightship.

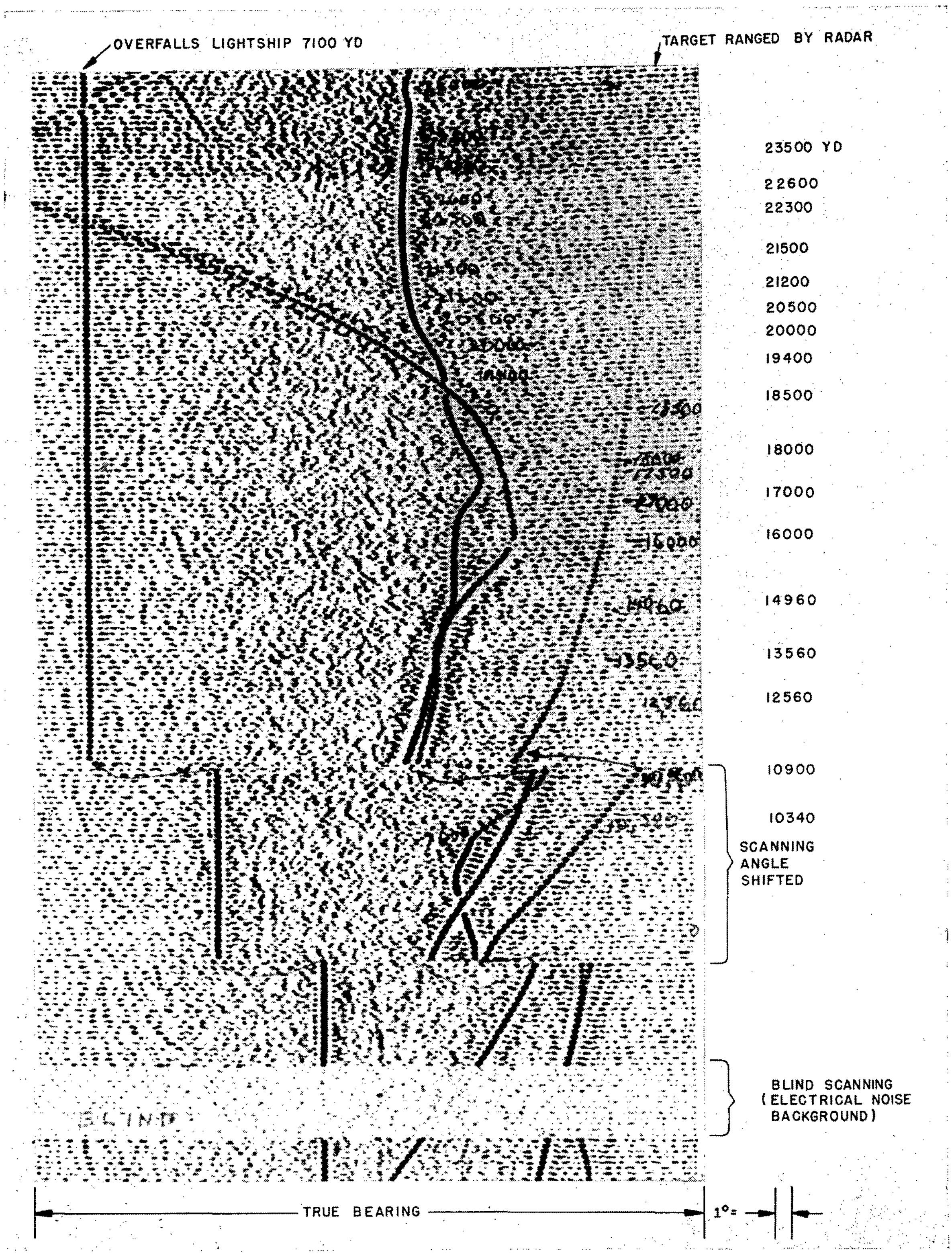


FIGURE 34. SSD record made at Cape Henlopen.

sector scanning. An improved, more powerful servomechanism required for the new recorder constructed for the dual operation of scanning heads was designed.

The first three nights of testing yielded little data of interest, due to light traffic and radar difficulties; however, continuous records were made. During the night of March 23, there were many targets and the radar (type SG–1) was in operation. The scanning head was mounted 15 feet above sea level and at this height ships, probably freighters, were detected and tracked up to ranges of 20,000 yards, even though at 18,000 yards the ships were 20 feet hull down. During these tests the temperature was 55 F and the relative humidity was 54 per cent (Figure 34). It will be noted from Figure 34 that a part of the record was made with a cover placed over the window. The signals written under this condition constitute the electrical noise background of the instrument. It will be seen that with the cover removed the general noise background is considerably increased; the increase is perhaps about 6 db. Hence, for these test conditions the thermal background set the limit of operation, and consequently greater sensitivity would not have given greater detection ranges. The effect of the thermal background might be reduced by decreasing the field of view, but for shipboard operation this is not practicable. Under these conditions the scanning speed might be increased without decreasing the threshold range.

Later during the same night with the SSD mounted 40 feet above sea level (distance to horizon 14,000 yards) and at an ambient temperature of 55 F and relative humidity of 74 to 80 per cent, passing ships, probably freighters and coastwise traffic, were detected and tracked up to ranges of about 23,000 yards. The section of the record shown in Figure 35 shows three vessels passing the mouth of Delaware Bay; the radar did not resolve the targets. In this record a surprisingly large signal is given by a can buoy at 3,250 yards.

TESTS ABOARD THE *Marnell* AND AT CAPE HENLOPEN, JUNE 5 TO 19, 1945

The final experimental model of the SSD equipment having an improved scanning head with a two-speed follow-up system was designed and constructed. This new head contains a much more rigid mounting for use on the stabilized platform, and a new follow-up system consisting of a servo motor geared to the rotating part of the head and to control transformers, operated at 1 and 36 speed. For this scanner, the drive unit, built by the Ford Instrument Company for the Bureau of Ships, consisted of a synchronous motor geared to 1- and 36-speed synchro differential generators. The course of the ship on which the test was made was put into the scanning motion electrically. The drive unit was linked mechanically with the recorder.

A second such scanning head, the mechanical drive of which was constructed by Bendix Marine to Harvard specifications under a Bureau of Ships contract, was also available.

The final experimental model of the SSD equipment was installed on the *Marnell* on June 5, 1945, at New York City. On the nights of June 6–7 and 7–8 the stable tables drifted, which necessitated frequent leveling of the scanning head in order to detect targets. Several targets were encountered on the night of June 7–8 and operational ranges were determined for a number of ships of unknown types under conditions of ambient temperatures of 55 degrees to 60 degrees, 2-centimeter precipitable water vapor content. The operating ranges varied from 6,300 to 14,000 yards.

On the night of June 9 an unidentified vessel was followed from New York to New London. Since the ship moved slowly it was possible to open and close range at will, thus making possible the determination of several threshold ranges. A portion of the SSD record is shown in Figure 36. During the 6-hour period, the bearing of the target was shown on the record when the range was not greater than 14,000 yards, except during a brief interval when the scanning rate was doubled (12 degrees per second); the threshold was then reduced to about 11,000 yards. From the ship's log the visibility was given as 2 miles for 5 hours of the run.

Extensive tests were made with a controlled DE target on the night of June 11–12 and on a controlled DD target on the night of June 12–13. There was apparently little difference between the atmospheric conditions on these two nights. The average detection ranges for the DE and DD were 8,030 and 8,250 yards, respectively, which indicate that the two vessels were approximately equivalent heat sources.

The data are analyzed in Table 8. It will be noted that for all aspects the average signal range was

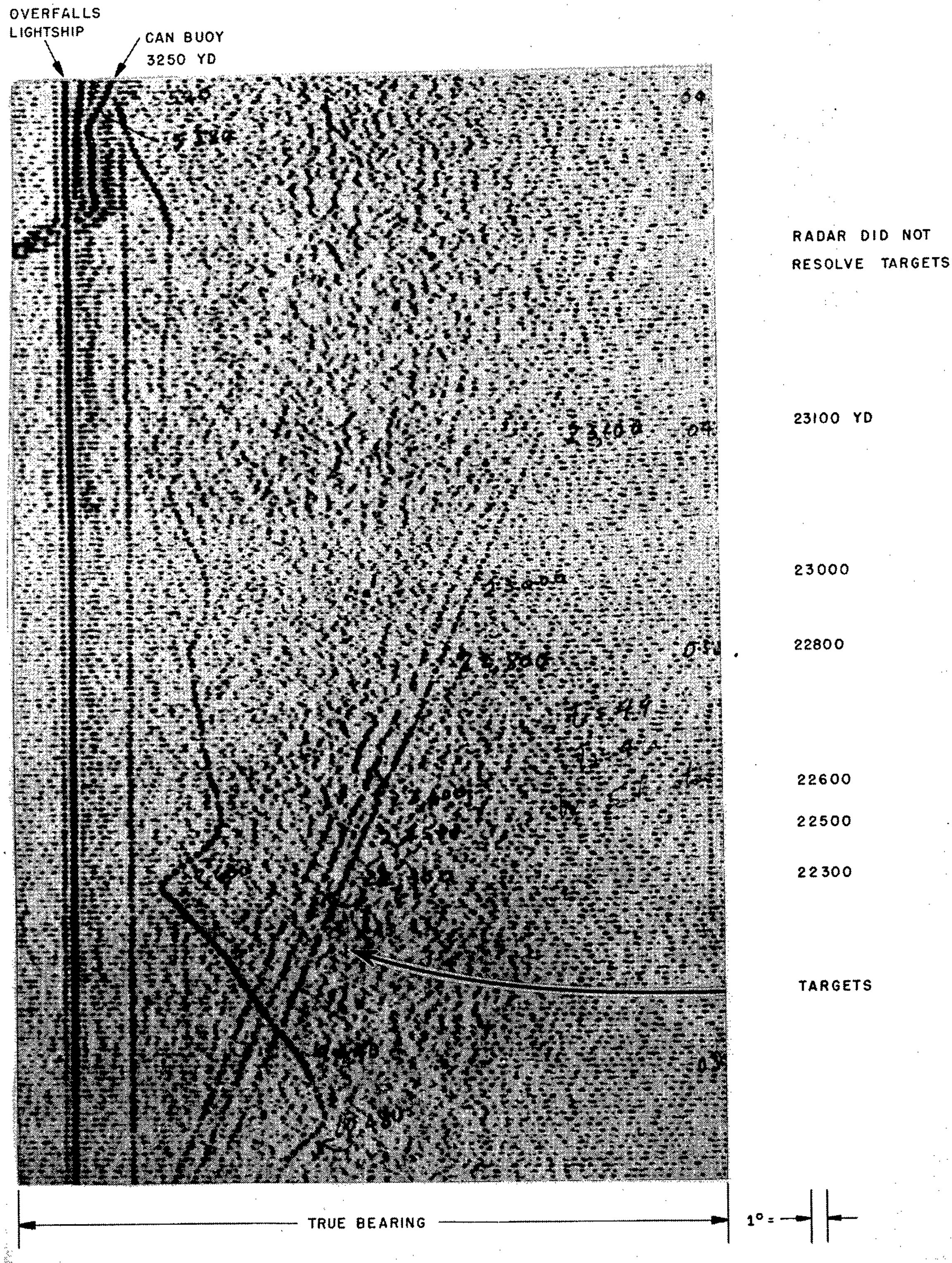


FIGURE 35. SSD record made at mouth of Delaware Bay.

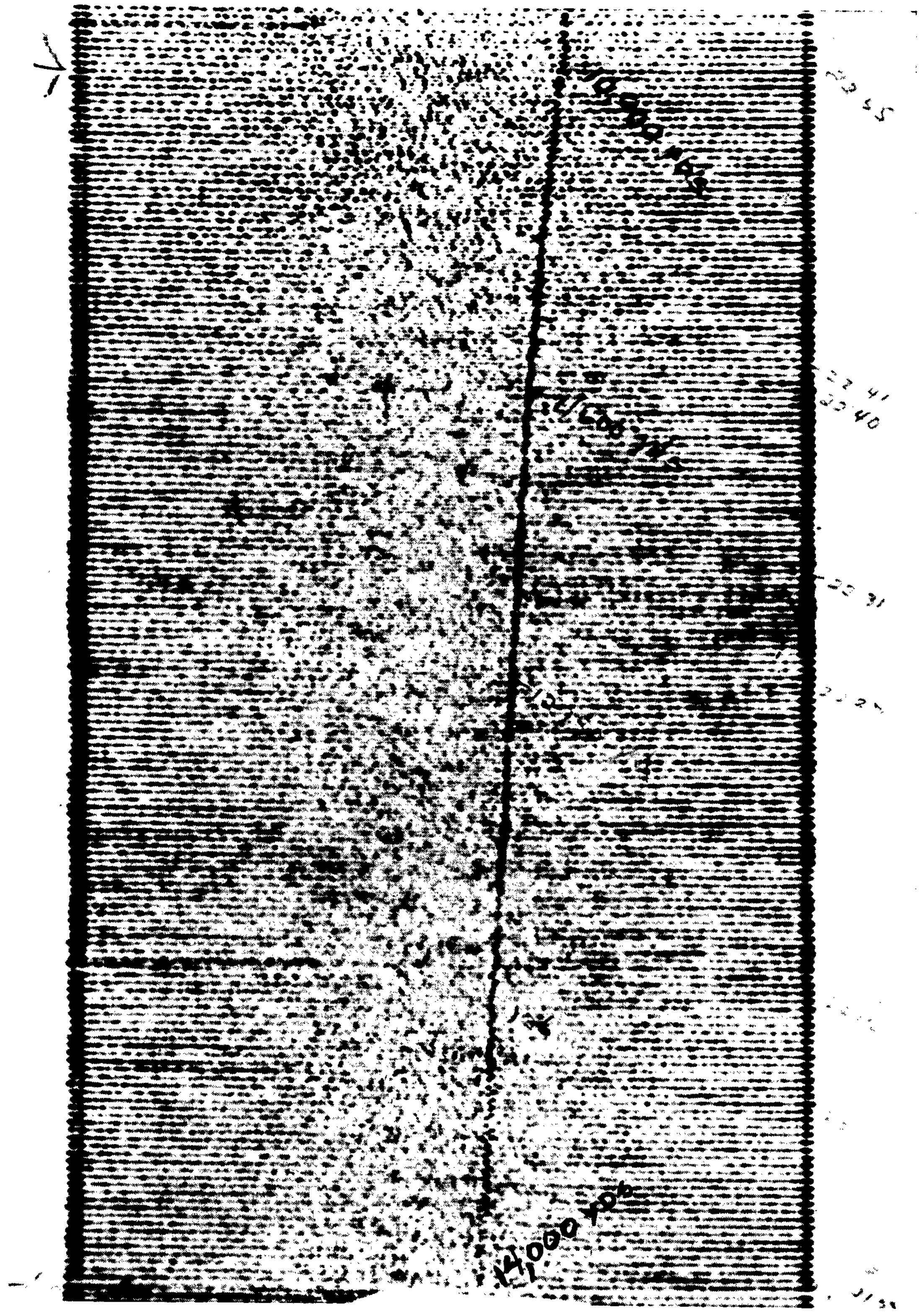


FIGURE 36. SSD record made aboard the *Marnell* near Cape Henlopen.

RESTRICTED

greater in these tests than in the October 1944 tests; also, the minimum signal range was appreciably greater in all cases except for bow aspect. During the October tests the maximum sector scanned was about 40 degrees or less, in order to scan the target more frequently. During the June tests the sector which was scanned was 60 to 65 degrees.

TABLE 8. Data taken aboard the *Marnell* and at Cape Henlopen, June 5 to 19, 1945.

		Definite Signal Range			Tracking Signal Range	
Aspect	Runs	Avg	Max	Min	Max	Min
Broadside	6	10,340	12,800	8,800	12,080	10,200
Stern	7	7,890	9,150	6,800	10,800	7,540
Stern quarter	5	8,930	9,700	8,000	10,900	9,600
Bow quarter	3	8,520	9,400	7,600	13,000	9,100
Bow	4	4,475	6,300	3,600	6,300	3,600
All aspects	24	8,100	....	....	....	....

Atmospheric conditions during these June tests were less favorable than during the October tests, due to considerable haze which existed during all of the test period. The average temperature was 60 F and from the ship's log the visibility was 5 miles on the night of June 11–12 and 5 to 10 miles on June 12–13. The water content of the atmosphere was 2.4 centimeters per sea mile. The sea was rougher during the June tests; the maximum values of roll and pitch recorded on the night of June 11–12 were 12 and 7 degrees, respectively. The *Marnell* yaws considerably under these conditions.

The greater ranges obtained during these tests may be attributed to the use of a cell having a larger aperture, to improvements in recording, and to more accurate correction for yaw and course.

A section of the record obtained during the night of June 13 is reproduced in Figure 37. This is one of the better records secured during the controlled target tests and shows the greatest bow range which was obtained. It is of interest to compare signal strengths at equal ranges for different aspects. It will be seen that the "bow signal" is definitely weaker than the "stern signal;" the relatively short ranges for bow aspect result from the combination of weak signals and the rapid closing of range. During two bow runs the range was closed at approximately 1,000 yards per minute.

In order to check the overall sensitivity of the equipment, the apparatus which was used in the March 1945 tests at Cape Henlopen was set up at the Bureau of Ships Test Station (Cape Henlopen) for comparison with that used on the *Marnell* in these June tests. There was no appreciable difference in ranges obtained with the two sets of apparatus. Typical ranges observed at the Test Station at an ambient temperature of 71 to 81 F for several different types of targets were as follows: U. S. cargo ships, 8,000 to 12,000 yards; pilot boats, 8,300 to 8,800 yards; tug, 8,900 yards; U. S. tankers, 7,600 to 11,000 yards; British tanker, 13,000 yards (the variation in range is due, in part, to varied aspects of vessel viewed). These ranges compare favorably with those which were obtained on shipboard. The haze conditions at Henlopen were similar to those encountered in the New York and New London areas. The precipitable water varied between 3.2 and 4.0 centimeters per sea mile at Cape Henlopen as compared to 2.0 to 2.4 centimeters per sea mile on board ship.

During the March test at Cape Henlopen, when 20,000-yard ranges were obtained, there was little or no haze and about 1.4 centimeters of water per sea mile.

9.10.5 Present Status

The stabilized ship detector was adopted by the Navy for operational use. Several production contracts were let for the manufacture of models of the SSD equipment. At the end of the war preproduction models of the different components of the SSD had been produced and were being given tests prior to the final design of the components for quantity production.

9.11 EXPLORATORY EQUIPMENT USING THE LEAD SULFIDE CELL FOR MILITARY PURPOSES

9.11.1 Introduction

The University of Michigan, under Contract NDCrc-185, was requested by Section 16.4, NDRC, to construct and test a preliminary device utilizing a lead sulfide [PbS] photoconductive cell as the sensitive element, for the detection of low-temperature military targets by means of their self-emitted thermal radiation.

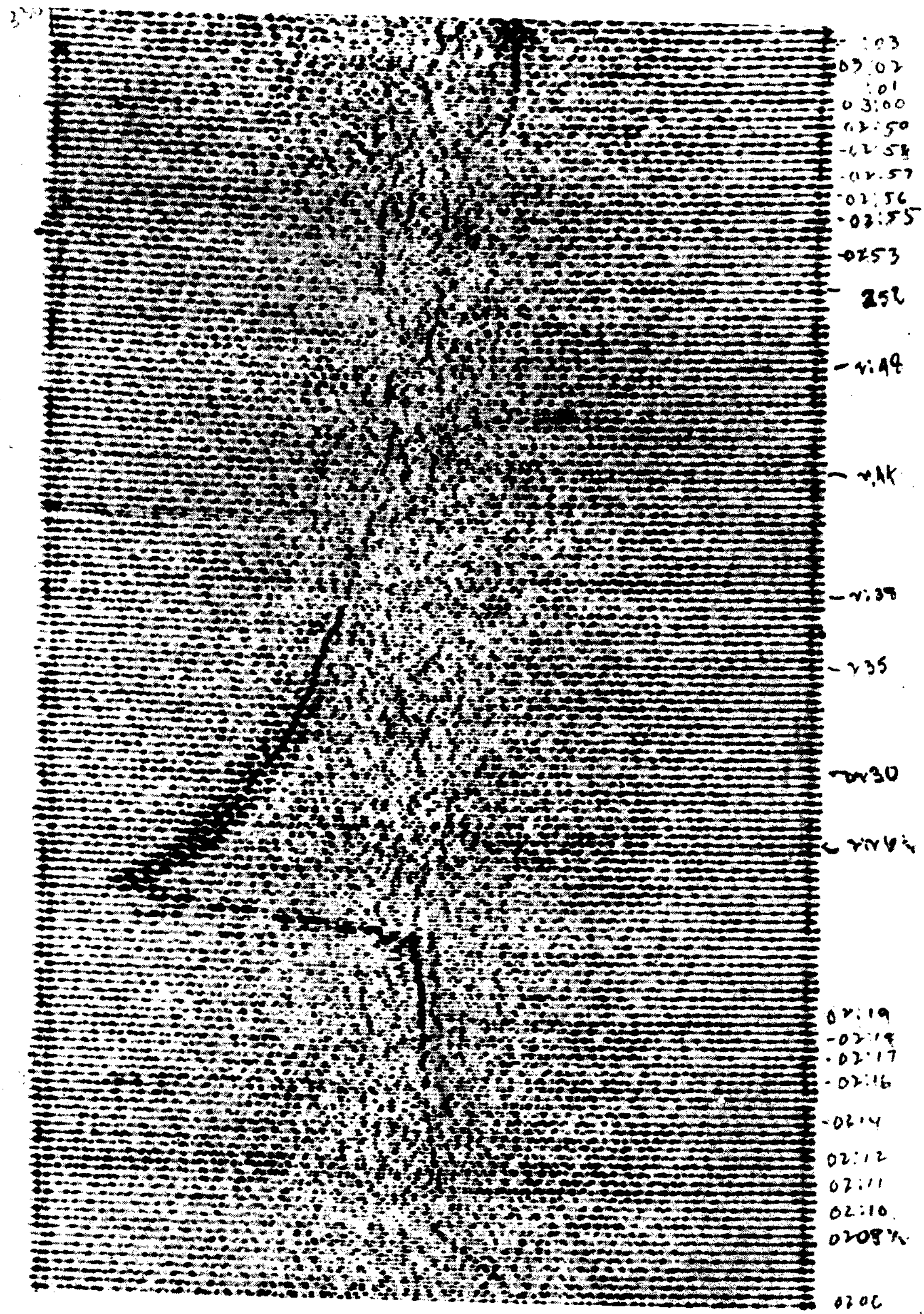


FIGURE 37. SSD record made aboard the *Marnell* near Cape Henlopen.

This section of Chapter 9 describes briefly an exploratory receiving apparatus using this type of cell, and the detection tests carried out with this equipment using men and ships as targets. Since the PbS cell is most sensitive in the intermediate infrared region, this equipment has been designated as the IIR (intermediate infrared) receiver.[21]

This exploratory test equipment consists of an oscillating mirror, 15 centimeters in diameter, which sweeps the minute field of view of the receiver through an angle of 0.015 radian about 55 times per second; the detector cell, its sensitive surface located in the focal plane of the mirror and cooled with solid CO_2; a battery-operated amplifier with which to amplify the electric signal produced when the image of a thermal discontinuity traverses the sensitive element, including a narrow passband circuit tuned to twice the frequency of the oscillating mirror to increase the signal-to-noise ratio; and a signal-output-indicator meter.

9.11.2 General Description

The apparatus which was designed consists in principle of an oscillating mirror with the sensitive surface of the PbS cell placed at the focal point. If the object subtends a sufficiently small angle, the apparatus is so aimed that the cell receives radiation from the background with the mirror in one extreme position, from the object when the mirror is at the center, and from the background again when the mirror reaches the other extreme position. The "scanning frequency" is about 55 c. This is twice the 27.5-c frequency of oscillation of the mirror, since the image of the source is swept across the sensitive element from left to right and also from right to left once in each complete oscillation of the mirror. When the amount of radiation received from the object is greater or less than that from the background, the resistance of the PbS cell is different while the mirror field of view includes the object than when the field of view includes only an otherwise uniform background. This results in a periodic electric impulse which, after amplification, operates the signal-output-indicator meter. A photograph of the apparatus is shown in Figure 38.

For radiation having wavelengths from 2.5 to 3.5 μ, this receiver was found to be capable of detecting a radiation flux density of about 10^{-12} watt per square centimeter, corresponding to about 10^{-10} watt incident on the sensitive element when cooled with solid CO_2. For a black-body source at temperatures near 50 centigrade degrees the total flux density necessary to provide this amount of power in the 2.5- to 3.5-μ band is about 400 times larger than the figure given above. This takes into account the total power radiated by such a source over all wavelengths, to much of which the lead sulfide detector is insensitive.

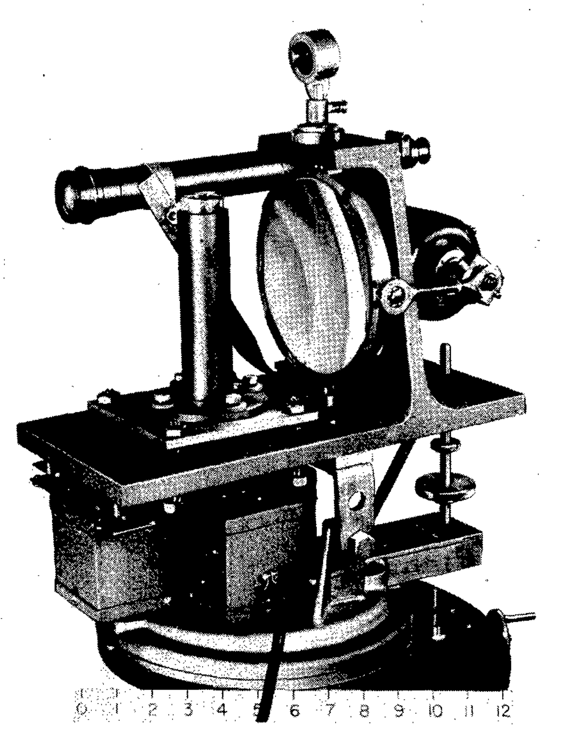


FIGURE 38. Photograph of intermediate infrared detector.

9.11.3 Description of the Component Parts

OPTICAL SYSTEM

The oscillating mirror and the driving motor are supported in an aluminum casting of special design. The precision quality, parabolic mirror has a diameter of 15 centimeters, a focal length of 6 centimeters, a circle of confusion about 1/64 inch in diameter, and is gold-plated to provide high infrared reflectivity. The sensitive surface of the PbS cell is brought to the exact focal point of the mirror by adjustment of the four screws on which the base plate of the cell and shield assembly is mounted.

The field of view of the receiver was determined by placing a flashlight bulb at a distance of 20 feet in front of the receiver and plotting the output signal in decibels against the angular coordinates of the "point source." The "effective field of view," defined as the region enclosed by the —6 db isodecibel line, when measured with reference to the maximum decibel reading obtained, has evidently one value when the mirror is stationary and another when it is oscillating.

With the mirror stationary, the point source was modulated by operation from an a-c power supply. The effective field of view determined experimentally by this method was approximately rectangular in shape, 0.0025 radian wide by 0.0125 radian high, and is hereafter called "the mirror field."

When the mirror oscillated, the scanning of the mirror field across the point source modulated the radiation incident on the detector. The height of the effective field of view was found to be the same as with the mirror stationary, but as expected, the width of the field was found to depend upon the scanning angle, which may be varied. This effective field of view is hereafter referred as to the "oscillating field." All the final tests were made with a scanning angle of 0.015 radian, which was found to produce an oscillating field width of 0.007 radian.

Scanning Mechanism

An adjustable cam, visible on the end of the motor shaft, drives the mirror through any desired scanning angle. The motor used is an 8-volt, 1/200-hp, d-c motor the speed of which on 6 volts is about 1,650 rpm, causing the mirror to oscillate about 27.5 times per second.

The optimum adjustment of the scanning angle so as to obtain the maximum output indication depends upon the angular size of the object which is to be detected. The relative time spent "on" and "off" the object on each side of the scan affects the wave shape of the signal and therefore the magnitude of its fundamental frequency component. The magnitude of the indication is proportional to the amplitude of only the fundamental component, which is in turn dependent upon the wave shape of the signal from the cell.

To produce a signal with a fundamental frequency of twice the oscillating frequency of the mirror, the instantaneous mirror field must scan through an angle equal to or greater than the sum of the angular size of the mirror field added to the angular size of the target. The maximum amplitude of this signal from a target occurs when the scanning angle is adjusted so that the time spent "off" the target on each side approximately equals the time spent in scanning across the target.

The Detecting Element and the Amplifiers

The lead sulfide photoconductive cell (described in Chapter 3) has been developed in this country by Northwestern University under Contract OEMsr-235.[22] The effect of background illumination on the response of the cell to a modulated signal is much smaller than for the thalofide [TF] cell. Typical cells made to date have a peak response near 2.5 μ and a long-wavelength threshold near 3.5 μ. A spectral response curve for one cell is shown in Figure 39.

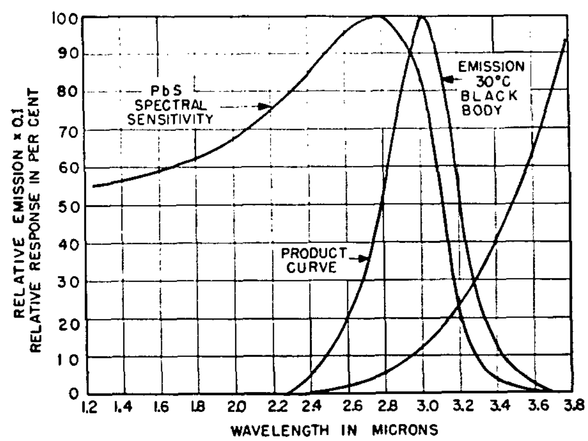


Figure 39. Spectral-response curve for photoconductive cell.

The responsivity of the PbS cell increases with a decrease in its temperature. Although the effect of cooling may vary from cell to cell, one cell showed a gain in signal-to-noise ratio of 25 db at the temperature of solid CO_2 as compared with room temperature.

Over a wide range the response of the cell is essentially independent of frequency; most cells show a practically flat response at room temperature to frequencies of from 30 to 1,080 c. When these cells are cooled the change of cell response with frequency is somewhat greater than at room temperature, but is still not so large as for TF cells; at 1,080 c the response from three PbS cells, cooled with solid CO_2, was down by 6, 7, and 8 db, respectively, as com-

pared with the response voltage at a signal modulation frequency of 90 c.

The cell used in the receiving equipment described herein was designed for cooling with solid CO_2. It had a sensitive surface about 0.3 by 1.5 millimeters. At room temperature its signal-to-noise ratio was 67 db for an incident flux of 1 microhololumen from a tungsten source operated at or near a temperature of 2848 degrees K, when the load resistor was 1 megohm and the applied voltage 22.5 volts. Its response at room temperature was 2.5 db less at 1,080 c than at 90 c.

The PbS cell is connected in series with a 5-megohm load resistance and a 45-volt battery so that any change in the resistance of the cell results in a corresponding change in voltage across the fixed load resistor. The fundamental frequency of this output voltage is the same as the scanning frequency (i.e., twice the mirror oscillation frequency). The wave shape of this voltage will depend on the relation of the angle of scan to the angular size of the object and to the angle of view of the mirror. This signal is transmitted to the amplifier.

The amplifier for the IIR receiver consists of three units: a preamplifier, a main amplifier, and a tuning section which plugs into the main amplifier. The preamplifier consists of a resistance-coupled amplifier, with self-contained batteries for plate and cell supply. A wire-wound load resistor for the cell was used in order to eliminate noise caused by the cell current passing through the load resistor. The remaining noise originates principally or entirely in the cell. The preamplifier is hung in a box beneath the casting to permit the shortest possible leads from the cell to the grid of the first tube. Antivibration mounts isolate the amplifier mechanically to avoid microphonics which otherwise might be caused by vibrations from the oscillating mirror.[23]

The main amplifier has been completely described in a contractor's report. It is entirely battery-operated, and consists of an audio-frequency amplifier with calibrated attenuators and an output decibel meter of the slow speed, rectifier type.

The amplifier tuning unit is a General Radio Company's type 760-A sound analyzer. It has a bandwidth, at the half-power points, of 2 per cent of the frequency to which it is tuned. This sharply tuned unit is used because the noise voltage appearing at the output meter is proportional to the square root of the bandwidth. Thus by tuning the narrow band-pass filter to the fundamental frequency of the signal, although the original wave shape of the signal is not maintained, it is possible to realize an appreciable gain in the signal-to-noise ratio.

The total possible amplification from cell to output meter is approximately 150 db. The gain necessary to reach the noise level of the PbS cell is approximately 100 db. The signal is read on a meter which is used as an indicator.

9.11.4 Threshold Sensitivity for a Low-Temperature Source

The spectral sensitivity curve for one PbS cell (not the cell in the IIR) is shown in Figure 39. Also shown are the spectral emission curve of a black body at 30 centigrade degrees and the product curve, on an arbitrary scale, of the 30 centigrade degrees black-body emission curve and the cell spectral response curve. The product curve shows that about 95 per cent of the response of this cell to radiation for a 30-centigrade degree source is due to only that part of the entire radiation which has a wavelength of from 2.5 to 3.5 μ.

Threshold flux densities which the receiver can detect, based on a signal-to-noise ratio equal to one, have been determined and are given in Table 9. The values given do not take into account diminution by atmospheric absorption but represent the energy densities at the receiver necessary to produce a signal equal to the noise.

TABLE 9. Threshold signal flux density for PbS receiver (black-body radiation distribution assumed from source at T centigrade degrees against uniform background at 25.5 C).

T (degrees C)	Microwatts/cm² (2.5- to 3.5-μ region)	Total radiation
30	1.02×10^{-6}	6.9×10^{-4}
40	1.02×10^{-6}	5.3×10^{-4}
50	0.95×10^{-6}	3.4×10^{-4}
60	0.80×10^{-6}	2.6×10^{-4}

9.11.5 Field Tests

PERSONNEL DETECTION

The purpose of the first test was to determine the ability of the IIR receiver to detect radiation from a man at night against a sky background and

against a foliage background for comparison with the reported sensitivity of the PND.[10] The tests were conducted near Ann Arbor, Michigan, on a hazy night with stars and moonlit sky; relative humidity was 94 per cent, temperature 59 F. A clothed man at 1,000 feet silhouetted against the sky produced a signal 15 db above the noise. The same man at 900 feet against a foliage background produced a signal 18 db above the noise. These were not threshold ranges and, therefore, indicate personnel detection ranges of the same order as those reported for the PND, with which a man can be detected against a foliage background at a maximum distance of 1,500 feet.

Ship Detection

A second field test was conducted to obtain experience on the detection of ships and to obtain some idea of the operation of the apparatus through several miles of atmospheric attenuation. This test was made at the Grosse Pointe (Michigan) Yacht Club, overlooking Lake St. Clair, on the night of October 2, 1945. The receiving equipment was located about 25 feet above the water level and freighters were observed as they passed up or down the ship channel. Bearings of the ships were taken with a transit at the time the ships were detected, and from a large scale map of the channel the approximate ranges were determined. The most distant target observed was a lighted freighter on the horizon about 8 miles away. It produced a signal 24 db above the noise. The lights on this ship were barely visible to the eye at this range, but it is believed that a large part of the detected signal came from these lights. Since it was not feasible to extinguish the lights and since for the 2.5- to 3.5-μ region no other means were available for isolating their radiation from that of the ship, a measure of the ability of the detector to respond only to the thermal radiation of the ship itself was not obtained.

The purpose of the third field test was to determine an order of magnitude for the detection range of a ship without lights. This test was conducted on the night of October 22, 1945, at the Bureau of Ships Test Station, Cape Henlopen, Delaware. An SSD [18] was operated simultaneously with the IIR receiver so that proper comparison could be made between the two, using the same target and target distance and under the same weather conditions. The *Callao*, a 1,000-ton steam-driven ship, 185 feet long and 30 feet wide, served as target. Its stack is about 5 feet in diameter, reputedly quite hot, and is equally visible when observing the port, stern, or starboard aspect of the ship. During this test there was a very light haze and a bright moon. The temperature was 64 F and the relative humidity 94 per cent. The *Callao* was detected at a maximum range of 4,400 yards with stern aspect. The corresponding threshold range for detection by the SSD was between 8,100 and 9,000 yards, or about twice that of the IIR receiver.

9.11.6 Evaluation of Results and Proposals for Future Work

The results of the Cape Henlopen test provide the only reliable data obtained on the performance of the IIR receiver as a ship detector.

The SSD is essentially a nonselective receiver which responds almost uniformly to equal amounts of radiant energy at any wavelength from the visible out to about 15 μ, the long wavelength transmission limit of the rock-salt window which covers the bolometer element. The maximum radiation from a low-temperature source such as a ship occurs near 9 μ and fortunately coincides with the well-known atmospheric transmission "window" from 8 to 13 μ. As a result, the greater part of the radiation to which the SSD responds lies within the "window" region of 8 to 13 μ.

The IIR receiver, on the other hand, is sensitive only to wavelengths no longer than about 3.5 μ. Only about 0.1 per cent of the total energy radiated by the ship is of shorter wavelength than 3.5 μ. Moreover, a strong water vapor absorption band overlaps the region from 2.5 to 2.8 μ and a weaker band extends from 2.8 to approximately 3.3 μ. Within the regions from 2.5 to 3.5 μ lies most of the radiation from the ship to which this receiver responds.

One may therefore say that, although the threshold sensitivity of the two receivers to black-body radition from a low-temperature source is about the same, the transmission characteristics of the atmosphere alter the spectral quality of the radiation from a low-temperature source, during its passage to a distant receiver, in such a way as to discriminate against the IIR receiver in comparison to the SSD. The high humidity at the time of the tests accentuated this discrimination.

9.11.7 Present Status

The promising results of the preliminary tests made with this exploratory apparatus appear to warrant further development of the PbS cell for use as a high-speed intermediate infrared detector. Moreover, the cooled-type PbS cell already developed under Contract OEMsr–235 apparently has sufficiently desirable properties to justify the further development of IIR receivers utilizing this type of heat-sensitive element for personnel detection, ship detection, or other military applications. Perhaps some other type of photoconductive cell could be found in which the sensitivity might extend out to about 4.5 μ.

Work has been initiated at Northwestern University under Contract OEMsr–235 in an attempt to develop cells (utilizing PbS and other materials) that are sensitive beyond 3.5 μ, in order to make use of the narrow atmospheric "window" in the region of 3.4 to 4.4 μ. On the basis of the test results described above, it seems likely that if such a cell is successfully developed, a receiver could be built having a greater range and a more rapid response than the other infrared detecting equipment now in use.

9.12 THE INFRARED RANGEFINDER

9.12.1 Introduction

Considerable interest existed within the Navy concerning the possibility of developing a far infrared (8 to 14 μ) device which, in addition to detecting a target by bolometric response to temperature differences between the target and its background, could also fix the distance of the target from the detector. This interest in an infrared rangefinder which could be used at night without detection by the enemy gave impetus to the establishment at Harvard University of a project to develop such a device. Contract OEMsr–60 was set up under Project Control NO–183 by a request from the Bureau of Ordnance.

The purpose of the project was the development of a rangefinder employing long-wave, thermal-type infrared radiation.

The equipment developed determines at night the range of a ship to 10 per cent or less and its bearing to 1 minute of arc or less. The equipment is effective to at least 5,000 yards.

Automatic horizontal guiding was a necessary auxiliary development to make the equipment useful on an invisible target. Up to 5,000 yards range, the equipment will automatically follow a target in the horizontal plane to less than 1 minute of arc.

Possibilities for improvement in the equipment are the following:

1. Increase in sensitivity.
2. Increase in accuracy of ranging.
3. Automatic vertical guiding and self-stabilization.

9.12.2 General Description

A simplified schematic diagram of the infrared rangefinder [24] is shown in Figure 40. This instrument operates on the principle of the standard optical rangefinder which determines the range R from the interocular distance and the parallax.

Heat radiations from a target ship T are focused on a sensitive bolometer at B. In this section, a bolometer and its associated optics are referred to as an *eye*. The electric signal generated at B by the heat radiations operates an automatic device which rotates the whole rangefinder about the point C and keeps the eye B always pointed at the target. Consequently, the other eye A is also pointed in the general direction of the target. However, if the eyes are parallel, it is necessary to rotate the eye A farther toward the target by the amount of the parallax angle. This further rotation of the eye is manually controlled by an operator so that both eyes are kept pointed always at the target.

In the case of the standard optical rangefinder the operator performs a similar rotation of one eye with respect to the other by the amount of the parallax angle. He judges when both eyes are correctly pointed by visual comparison of the images which they form. He reads the range from a dial which is moved in accordance with the parallax angle rotation. In the case of the infrared rangefinder the electric signal received at B is compared electronically with that received at A, and the result registers on a meter. The operator judges when both eyes are correctly pointed by observation of this meter. The parallax angle is read from a dial which moves in accordance with the parallax angle rotation of the eye A. The parallax angle is related to the range R and the interocular distance Z by the expression $\beta = (Z/R)$, β being the parallax angle.

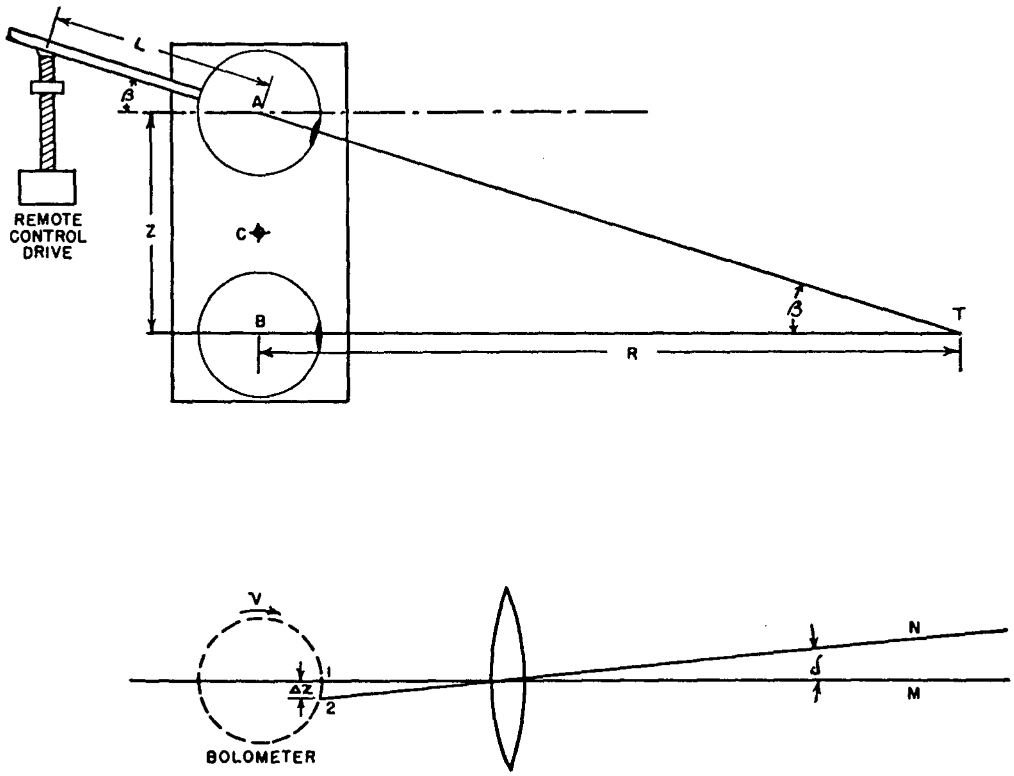


FIGURE 40. Schematic diagram of infrared rangefinder.

The detectors at points A and B are rotating squirrel-cage type nickel strip bolometers. This instrument consists of a number of very thin, blacked nickel strips spaced evenly around the surface of an imaginary cylinder, the strips being parallel to the vertical axis of the cylinder about which the strips rotate with a constant speed v.

AUTOMATIC FOLLOWING

The schematic diagram, Figure 40, illustrates how bolometer B keeps the rangefinder pointed at the target. When the lens is pointed directly at the target, radiations arrive along its optical axis M, and an image of the target is focused at point 1. As each nickel strip sweeps through this target image, it is heated by the radiation. The strips are connected so that the successive heating of each strip produces a small alternating voltage in the associated circuits. If the lens is not pointed directly at the target, the radiations will arrive along some other path, such as N. In this case, the image will be formed by the lens at the point 2. The angle between the radiation path N and the optical axis M is called the guide angle δ.

The bolometer measures this small displacement δ of the image in the following manner. Each strip arrives at point 2 somewhat later than it arrives at point 1. Consequently, the alternating voltage wave produced by an image at 2 will be shifted in time relative to a hypothetical wave produced by an image at 1. This time shift is a measure of the image displacement Z. The amount of the time shift is determined by comparing the bolometer signal with the signal produced by a generator. This real generator signal takes the place of the hypothetical signal produced by an image at 1. The comparison is performed by an electronic phasemeter whose d-c output voltage is proportional to the image displacement ΔZ, and consequently to the guide angle δ. This voltage operates an amplidyne system which rotates the whole rangefinder about the point C in a direction such as to bring the optical axis M onto the target and reduce the guide angle to zero.

RANGING

When the automatic following device is operating correctly, the eye B is kept pointing directly at the target. The operator rotates the other eye A to the

proper parallax angle in order to make it also point directly at the target (see Figure 38). A second phasemeter compares the alternating signal from eye B with that from eye A. The d-c output voltage of this phasemeter is zero when both eyes are pointed correctly. The operator accomplishes the rotation of eye A by remote control and reads the amount of rotation from a dial on his instrument panel. In the present experimental model, the range is determined indirectly from the dial reading by means of a table. It would be possible to engrave ranges on the dial so that they could be determined directly, just as in the standard optical rangefinder.

9.12.3 Description of the Component Parts

The Optical System

Figure 41 shows a photograph of the rangefinder, and Figure 42, a diagram. As shown in the diagram, the bolometers are actually not separated but are constructed coaxially on a single rotating shaft. This construction is advantageous because, if one bolometer were placed at each end of the rangefinder, it would be necessary to provide for exact synchronization of their rotations.

Radiation is focused on the bolometer by a fast parabolic mirror (12-inch diameter $f/1.0$), represented in the simplified diagram, Figure 40, lower, as a lens. The mirror marked A in Figure 42 points directly out to sea. A tangent screw at the end of the lever arm L is employed to change the angle of this mirror with respect to the rangefinder; i.e., to change the parallax angle. This tangent screw is remotely controlled with a selsyn type motor as explained earlier. The second mirror B points along the rangefinder to a double mirror (penta reflector) which redirects its view to sea. The penta reflector virtually separates the fixed eye B from the movable eye A by a 15-foot interocular distance. In the photograph (Figure 41) the penta reflector is in the box at the left end and the unit at the right end contains the bolometers, parabolic mirrors, and associated gear. This unit at the right is referred to hereafter as the head. The photograph is taken looking at the front of the rangefinder.

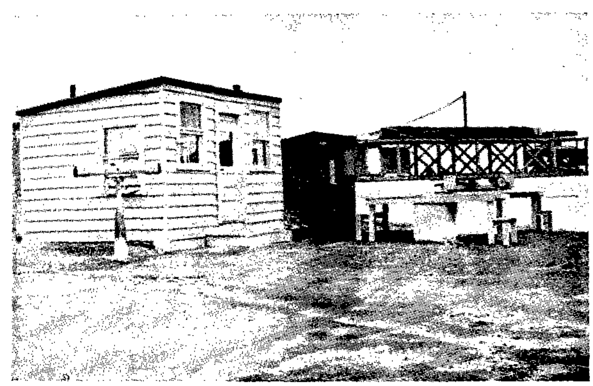


Figure 41. Photograph of rangefinder.

Description of the Bolometer

The two squirrel-cage bolometers are mounted, one directly above the other, on the same rotating shaft. The various stages of bolometer construction

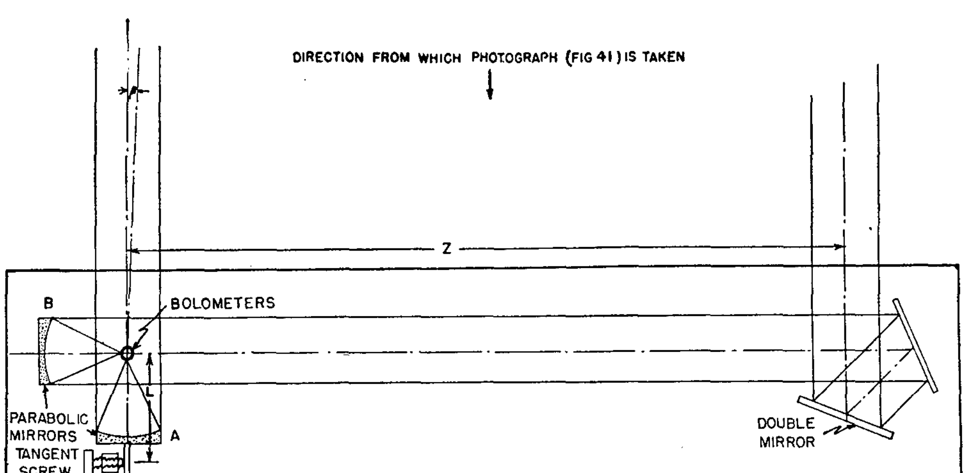


Figure 42. Diagram of rangefinder.

and assembly are shown beginning at the left in Figure 43, and a complete double bolometer appears at the extreme right.

The strips are spaced at the rate of 24 for the full circumference of each bolometer; but of these, only 8 strips are actually present. The individual strip is soldered at each end to a flattened silver wire. The supporting silver wires are held between two concentric brass rings pressed onto the shaft. The wires are insulated from the rings by mica sheets. These rings and the shaft are shown at the left end of the ruler in Figure 43.

At the next stage of construction (shown just below the 1-inch mark on the ruler), the outer brass ring has been cut out in the center of each bolometer to expose the silver wires beneath the outer mica sheet.

At the third stage (3½ inches on the ruler) the outer brass ring has been turned to diameter, the silver wires have been cut through, and the inner brass ring has been relieved, by turning, to provide an open space for the strips. Each strip is suspended across this open space in such a way that it replaces that part of the silver wire which has been cut away. Eight of the 24 possible strip positions are utilized for active strips, and in the case of the upper bolometer, three of the possible strip positions are shorted to conduct the signal from the lower bolometer to the top of the shaft. The signal leads for both bolometers go out through six holes in the top end plate of the casing.

In the center of Figure 43 at 5½ inches on the rule are shown the various parts of the bolometer casing. The long cylindrical silver tube shown second from the bottom is slipped over both bolometers. The end plates shown above and below this tube are slipped over the ends of the shaft.

In the next assembly (shown below the 9-inch mark on the ruler) the strips have been installed and covered with aluminum black, the casing is in place, apertures have been cut in the silver tube opposite each set of four strips, and a charcoal trap has been attached to the lower end of the shaft. The four apertures are covered with two AgCl win-

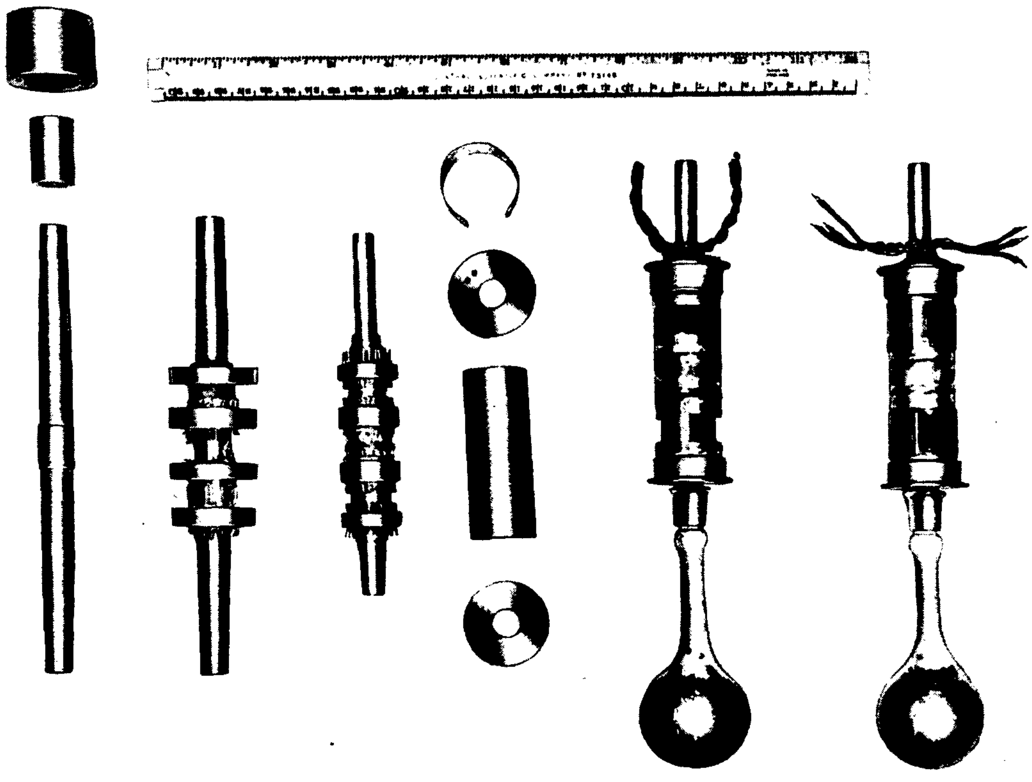


FIGURE 43. Figure showing various stages of bolometer construction.

dows (protected from solarization by gilsonite). One unattached AgCl window is shown at the top center of Figure 43. The glass seal-off which does not show clearly in the photograph is located just above the charcoal trap.

AMPLIFIER SYSTEM

Bolometer Bridge. The plus and minus bolometer strips connected in series form two arms of an a-c Wheatstone bridge; the other two arms are provided by the two halves of the primary winding of the input transformer. By connecting the two Wheatstone bridges in series a common battery can supply both bolometer circuits with current. This battery consists of two 1½-volt dry-cell units in parallel.

The strips which comprise the bridge arms are individually matched so that each has approximately the same resistance (about ¾ ohm). In the absence of radiation, the bridge is balanced. The opposite current flow in the two halves of the transformer primary produce opposing fields in the core and prevent saturation.

Strips of opposite polarity are placed adjacent to one another in the bolometer. Consequently, as the target image is scanned by the strips, an alternating unbalance of the bridge takes place. This alternating voltage which appears across the primary winding of the transformer induces an alternating current in the secondary winding which is carried by the line to the preamplifier in the instrument house. The turns ratio of the transformer is chosen to match the bolometer impedance (about 6 ohms) to the line impedance (500 ohms).

Each bolometer consists of two groups of four active strips separated from each other by two groups of eight phantom strips. Consequently, when the bolometer scans past the target image the resulting transformer output signal consists of a coherent wave train of two full cycles followed by a four-cycle gap, and then another wave train of two more full cycles, etc. In other words, no signal is produced when the target image scans past the phantom strips. The amplifiers in the instrument house are sharply tuned and have a long time constant (about one second) so that the amplifier output is a continuous wave train. The bolometer rotation frequency is 200 rpm and the signal frequency is 40 c.

Amplifier Circuit. The preamplifier is direct-coupled to the tuned amplifier so that it is convenient to discuss both of these circuits together. The signal is brought to the preamplifier by the 500-ohm line mentioned earlier. A transformer matches the impedance of this line to the grid of a pentode amplifier stage. The output of this stage is capacitance-coupled to the grid of a triode cathode-follower stage. A logarithmic attenuator is inserted between the pentode and the triode to serve as a gain control.

The second stage of the preamplifier is directly coupled to the cathode of the input stage of the tuned amplifier. A common cathode impedance serves both stages. This input stage is another pentode amplifier the control grid of which is connected to the output of a twin-T feedback network. The pentode is direct-coupled to the grid of a triode cathode-follower stage. The output of this second tuned-amplifier stage is applied both to the input of the feedback network and directly to the cathode of the third stage. The third (pentode amplifier) and fourth (triode cathode-follower) stages are essentially a repetition of the first two stages with a separate twin-T feedback path to the grid of the third stage. The two twin-T units in series combine to produce a high-gain, sharply tuned, 40-cycle amplifier. The values of the circuit elements in the second unit (third and fourth stages) differ from the corresponding circuit elements in the first unit because the amplifier is direct-coupled throughout. The output is taken from a cathode-follower stage and has a correspondingly low output impedance. The twin-T networks are tuned with a gang of eight rheostats all mounted on a common shaft. The tuning range is from 38 to 42 c, and the bandwidth at 40 cycles is between one-half and two-thirds of a cycle.

Phasemeter Circuits. Each tuned amplifier feeds directly into an amplifier-limiter, and each pair of amplifier-limiters feeds into a differentiator and trigger circuit. Such a combination of two amplifier-limiter channels followed by a differentiator and trigger circuit is referred to in this report as a phasemeter. A double-diode at the input of the amplifier-limiter circuit operates with fixed battery bias (±1.5 volts) to limit the signal. This limited signal is applied to the grid of a pentode amplifier which is operated at comparatively low gain. The output of this amplifier is limited again by a similar double-diode biased by the same source as the input

stage. A triode follows the second limiter and is used as a phase-inverter. The output signal may be taken from either the plate or cathode in order to make available a 180-degree phase inversion, as needed. The signal proceeds through another low-gain pentode amplifier and double-diode limiter to the final output. The circuit is capacitance-coupled throughout.

There are two inputs in the differentiator and trigger circuit, each of which is fed by a separate amplifier-limiter channel. The first stage in each case is a comparatively low-gain pentode amplifier. This is followed by a resistance-biased double-diode limiter stage. At this stage any usable signal has a good square waveform. The last limiter is followed by a differentiator network (RC = 25 μsec). The negative pulses from the two differentiator circuits operate the trigger circuit alternately. The trigger circuit, which comprises four pentodes, is an adaptation of the fundamental Eccles-Jordan circuit. A zero-center, 1-milliampere meter in the cathode circuit measures the average cathode-to-cathode potential difference.

It is an important characteristic of the instrument that noise variations in the input signal average out to zero reading of the indicating meter if they are completely random. If both input signals consist solely of random noise, the meter will fluctuate about zero and will have a zero average value. If the noise is superimposed upon two signals having a non-zero phase difference, it will cause fluctuations about that value; but the average value of the reading will be a true measure of the phase difference between the two signals. However, if the noise has a phase coherence, that is, if the phase relation between the noise superimposed on one input signal and the noise superimposed on the other is not completely random, then the phasemeter reading will be affected by the noise. It is important to eliminate all sources (microphonic, radiative, etc.) of non-random noise.

Amplidyne Control Circuit. The output of the bearing phasemeter is taken to the amplidyne control circuit. This is taken, as before, from the cathodes of the trigger tubes.

The signal is fed to a push-pull power amplifier circuit. The amplidyne field winding is the plate-load impedance. The gain control is located in the cathode circuit. With zero input signal (both control grids at the same potential) it is necessary to balance the plate currents so that the amplidyne meter will not run. This balance is accomplished by adjustment of the screen potentials with the potentiometer shown in the diagram. In order to ascertain (without turning on the amplidyne generator) whether the plate currents are properly balanced, a twin-indicator electron-ray tube (magic eye) is employed. This indicator is coupled to the amplidyne field winding by a double-triode cathode-follower stage which supplies the proper operating potentials to the indicator. It was mentioned earlier that the rangefinder lags a uniformly moving target. It is possible to compensate for such a lag by adjustment of the (screen) balancing potentiometer.

The amplidyne control chassis also contains a selsyn-type receiver. It is geared to a dial graduated in degrees which indicates the true bearing of the rangefinder. A number of relays and selector switches permit the application of suitable signals to the push-pull grids for continuous scanning be-between selected bearing limits. Another circuit operates off the signal-level meter to allow automatic break-in. That is, a signal of a predetermined level causes the amplidyne circuit to cease scanning between limits and commence following automatically the target which produced the signal.

The Representation Unit

Leads brought out from the trigger tube cathodes in the range phasemeter are taken to the d-c amplifier. The d-c amplifier circuit has been adapted from a standard balanced-triode circuit by placing the load impedance in the cathode circuits. The Esterline-Angus 1-milliampere recorder operates with series resistance as a d-c voltmeter to measure the cathode-to-cathode potential. The recorder sensitivity can be adjusted by means of a rheostat, the sensitivity usually being adjusted so that one small division on the record chart corresponds to a motion of the tangent screw of 0.002 inch. The balancing potentiometer connected between the two cathode resistors can be adjusted to place the phase zero at any desired position on the record chart.

9.12.4 Field Tests on the Infrared Rangefinder

On October 3, 1944, an official demonstration of the rangefinder was held for NDRC and Service representatives. Both manual and automatic track-

ing were employed and good results both in accuracy of tracking and accuracy of range were obtained on the tug target.

Tests on Controlled Target

Operating Procedure. Figure 44 is a reproduction of typical records taken during a controlled target test on October 3, 1944. On the left is a record of the output of the range phasemeter, and on the right is a record of signal strength as received by the fixed eye *B*.

The sensitivity of the phasemeter is adjustable. It has been adjusted so that one small lateral division on the range phase record is equivalent to a motion of the tangent screw of 0.002 inch. The phase zero, that is, the point on the scale that corresponds to the case where both eyes are pointing directly at the target, is represented by the heavy line near the right border. The record begins at the bottom of the page, and each of the curved horizontal lines marks a 30-second time interval.

The signal strength is shown on the right and is recorded logarithmically on a scale such that one small lateral division is equivalent to a change in signal level of 1 db. The average noise level is represented by the line 5 db to the right of the left border. This record also begins at the bottom of the page and is synchronized in time with the phasemeter record.

At the beginning of these records the rangefinder was fixed on the calibration source Dog, which consists of an electrical heater at the focus of a 36-inch mirror located 5,000 yards from the rangefinder at Nahant. From the record it is evident that the signal received from this source is 26 db above the average noise level. Since the range of this source is known to be 5,000 yards, the proper setting of the tangent screw can be calculated. When the tangent screw is adjusted to this position the range phasemeter record shows a constant deflection which is taken to be the phase zero, and the record has been marked accordingly. This deflection will result whenever both bolometers are receiving radiation from the target along their respective optical axes, i.e., whenever both eyes are looking directly at the target. The particular value of this zero deflection has no significance. It depends on several factors which will be discussed later in connection with bolometer construction. Means have been incorporated within the phasemeter for arbitrarily changing this zero to any desired point on the record; for example, the center. As mentioned earlier it is possible to incorporate optical calibration means in the rangefinder. This would obviate the necessity of a distant calibration source, such as the Dog.

After this calibration (which required 1 minute of time) the rangefinder was turned from the Dog to the controlled target. The target ship was the tug *Francis C. Hersey* of the Boston Tow Boat Company. The target ship was to make a number of runs at approximately constant range. In each case the ship was to return over substantially the same course to its starting point before going to the next range. The records shown in Figure 44 correspond to one of these constant-range runs. Actually, the range varied from about 2,500 yards to about 3,000 yards during this particular run. The rangefinder followed the ship automatically throughout the entire course.

The signal-level record indicates that the signal was about 30 db above the noise level when the target was first picked up (time, 1⅓ minutes). Thereafter, it increased slowly to a maximum of 34 db (time, 3½ to 4 minutes) and then decreased to about 27 db above the noise level (time, 7½ minutes). During this time the ship had traveled about 1,500 yards and increased her range by about 350 yards. Near the end of the records (time, 8 minutes) the target ship turned around in order to reverse her course. This is indicated by the coding mark at the left edge of each record. When the ship turned, the change in aspect caused the signal level to fall to a point only 22 db above the average noise level. This influence of aspect on signal level is one explanation of the variable character of the signal-level record. However, the predominating cause is presumed to be the influence of the gustiness of the wind on stack temperatures. The steady character of the signal received from the Dog at the beginning of the record demonstrates that these variations are not characteristic of the equipment. It should be noted that the range phase is independent of the signal level. This independence is particularly striking when the ship turned around (time, 8 minutes) producing the strong dip shown by the signal-level record.

When the rangefinder was moved from the Dog to the target ship (time, 1 minute) a large transient appeared on the range phase record. After this transient died out the record stabilized at a point seven

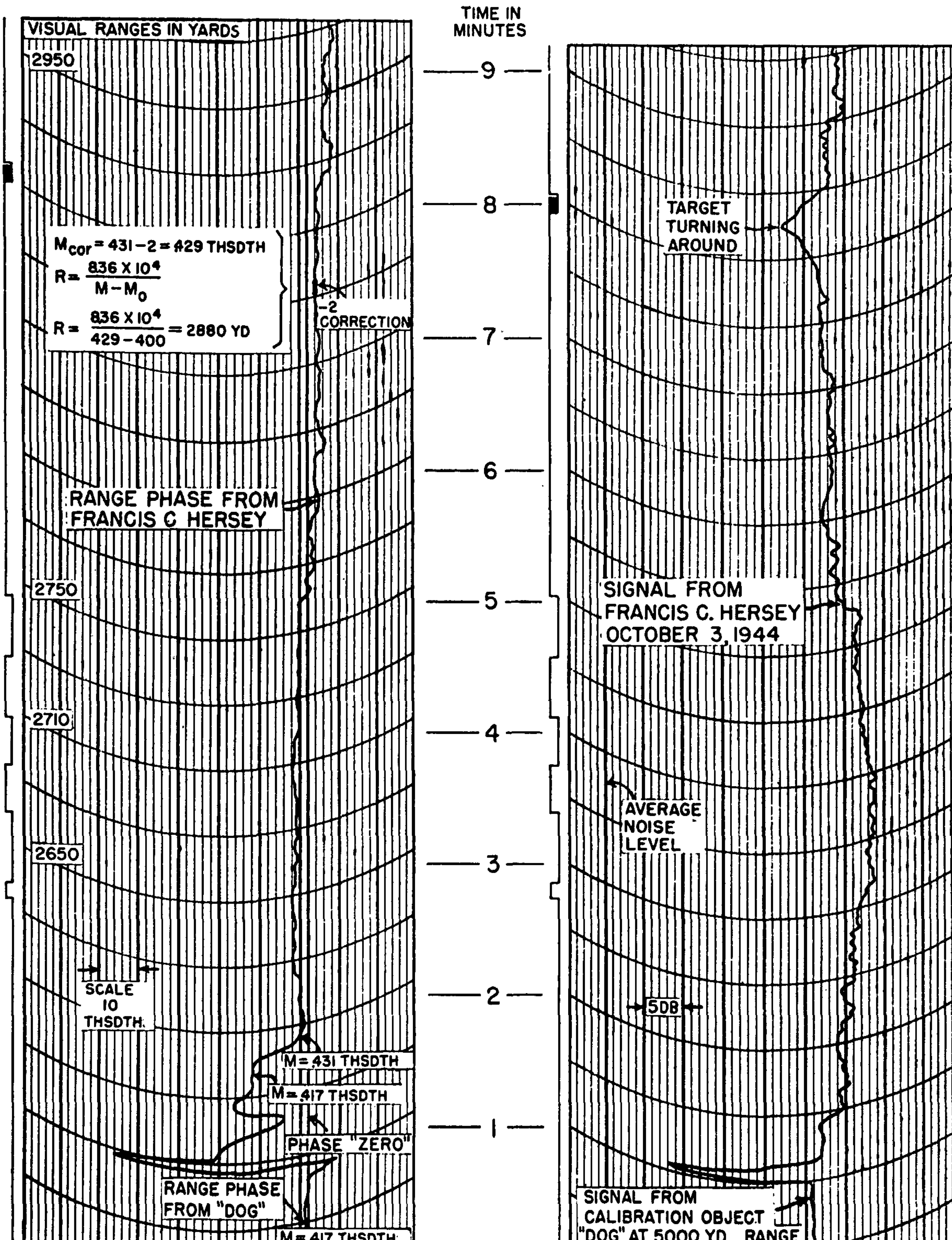


FIGURE 44. Record made by rangefinder corresponding to a constant-range run.

divisions (14 thousandths) to the left of the previously determined phase zero. At this time (time, 1¾ minutes) the tangent screw was still at its former value of 417 thousandths. The sign of this displacement of the range phase record from zero is an indication to the operator that the range of the ship is less than that of the Dog. Therefore, the parallax angle for the ship must be greater than that for the Dog, and the tangent screw displacement must be increased accordingly to return the phase record to zero. The notation $M = 431$ (time, 2 minutes) indicates that the operator turned the eye until the tangent screw dial read 431 thousandths. It was permitted to remain at this value for the duration of the run.

It will be observed that the fluctuations in the record with the present apparatus would make it difficult for the operator to maintain a constant phase zero reading by continual readjustment of the tangent screw. Consequently, it is customary for him to allow the tangent screw to remain fixed at some value which will keep the phasemeter record within a few thousandths of the phase zero. As the range of the target varies, the operator changes the position of the tangent screw from time to time in order to maintain this condition. The steady drift of this particular record from left to right is evidence that the range of the target is slowly increasing and that it will soon be necessary to readjust the tangent screw.

At any moment when the record actually corresponds to the phase zero, the range may be calculated directly from the reading of the tangent screw dial. Whenever the record departs from zero, it is necessary to correct the reading of the tangent screw dial by the amount of this departure before calculating the range. An example of such a calculation is shown on the record at a point 7½ minutes after the start of the run.

At the left edge of the phase record there appears a column of visual ranges. These were obtained with a 1-meter Bausch and Lomb coincidence rangefinder (Mark 57). Interpolation of these visual ranges for the points 5 and 9 minutes after the start of the run yields a value of 2,875 yards for the point 7½ minutes after the start. At this point the FIR rangefinder gave a value of 2,880 yards.

A set of visual and infrared range findings were recorded simultaneously during the tests on this night, and these are set down in Table 10. The result may briefly be summarized by stating that the infrared ranges varied within about 10 per cent of the ranges determined visually.

Performance of Automatic Following

The automatic following equipment operates as a continuously variable closed system. The discussion of this subject under "Automatic Following" and "Ranging" in Section 9.12.2 explains how the fixed eye B is used to measure the guide angle δ. As a result of this measurement the bearing phasemeter produces a d-c voltage which is directly proportional to δ. This d-c voltage is fed into an amplidyne system which in turn rotates the rangefinder

Table 10.

Time (minutes)	M (thousandths)	M corrected (thousandths)	R_{IR} (yards)	R_{VIS} (yards)	Error (yards)	Error (per cent)
1½	14	431	2700	....	....	...
2	2	433	2520	....	....	...
2½	4	435	2390	....	....	...
3	4	435	2390	2650	−260	9.8
3½	3	434	2460	2680	−220	8.2
4	4	435	2390	2710	−320	11.8
4½	3	434	2460	2730	−270	9.9
5	2	433	2520	2750	−230	8.4
5½	−1	430	2790	2775	15	0.5
6	−3	428	2990	2880	190	6.8
6½	−3	428	2990	2825	165	5.8
7	−3	428	2990	2850	140	4.9
7½	−2	429	2880	2875	5	0.2
8	−3	428	2990	2900	90	3.1
8½	−4	427	3100	2925	175	9.1
9	−5	426	3220	2950	270	9.2

with a velocity which is directly proportional to the d-c voltage. The rotation of the rangefinder changes the guide angle δ. The significance of these relations is that the velocity of rotation of the rangefinder is proportional to the guide angle δ.

The relations discussed in the preceding paragraph have been oversimplified by neglecting the time lags. The electronic portion of the system is characterized by a relaxation time of the order of 1 second due principally to the sharply tuned amplifiers. This means that when the guide angle δ changes, the d-c voltage lags this change by an amount approximately equal to the relaxation time. The amplidyne and mechanical portions of the system are also characterized by a finite relaxation time. This means that when the d-c voltage changes, the rangefinder rotation velocity lags the change in the d-c voltage. The effect of these time lags is cumulative. The d-c voltage corresponds not to the actual δ but to the guide angle of an earlier time. The rangefinder velocity corresponds not to the actual d-c voltage, but to the voltage that was present at an earlier time. Therefore, the rangefinder velocity is not directly proportional to the guide angle, but corresponds to the guide angle of a cumulatively earlier time. As a result, the automatic following system may exhibit a transient hunting period characterized by an exponentially damped oscillatory wave.

The rangefinder, when it is following a target which moves *uniformly* in bearing angle, lags it by a constant angle which is proportional to the rate of change in bearing of the target. This lag is evident to the operator on the bearing phasemeter. Electric compensation can be introduced by the operator to make the rangefinder follow the target exactly. The amount of this lag on the night of October 3, when the tug was moving laterally with a speed of 10 knots at a range of 2,000 yards, was 50 degrees in phase, which amounts to a guide angle of about ten minutes of arc.

An inherent defect of the 24-strip, squirrel-cage bolometer is the presence of multiple horizontal fields; that is, bearing phasemeter readings are the same for several angular positions of the target. These multiple fields are a result of the fact that several image positions on the bolometer give a signal with the same phase relation to the generator signal and the amplidyne system will follow on any one of the zero-phase points. It may also be made to follow at any intermediate point by the introduction of suitable bias and phase shifts. In order to locate an invisible target in the central field, it is necessary for the operator to scan deliberately across the outer fields before changing the servo control from *scan* to *follow*. Thereafter, the amplidyne system will follow at the point O.

The number of strips exposed to the target field is proportional to the total number of strips. If the number of strips were reduced from 24 to 6, the number of horizontal fields would be reduced from 5 to $1\frac{1}{4}$.

The amplidyne following mechanism operates on receding targets until the signal is almost obscured by noise. On the night of October 3, the tug *Francis C. Hersey* was automatically followed to a range of about 7,500 yards before it was lost. On the night of October 19, targets were followed successfully for several minutes when the signal was apparently equal to the noise. Under these conditions the rangefinder fluctuated about the target position with an amplitude of about 10 minutes of arc.

Similar tests were made on the nights of September 8 and 11 and October 2 and 19. These additional tests gave range accuracies and automatic-tracking performance equivalent to those obtained on the night of October 3 at the official demonstration.

9.12.5 Present Status

The successful tests carried out on the infrared rangefinder have led to a further development of the device. The New York Navy Yard has undertaken the engineering development required to adopt the present model of the rangefinder for shipborne use and for the construction of a pilot model. Consultation for this work was provided by the Harvard contract.

9.13 SPECTROPHOTOMETRIC ELEMENT, TYPE T [SETT]

9.13.1 Introduction

The development of a detector, for use in the infrared spectrometer for the recording of infrared spectra, which would be free from thermal drift and uninfluenced by vibrations was an item of extreme importance to industrial concerns involved in the

production of aviation gasolines, synthetic rubbers, and other chemicals used in the successful prosecution of the war. Previous methods employed sensitive thermocouples in conjunction with a high-sensitivity galvanometer relay. This method, although highly successful in the past in university laboratories, has the objection that the recorder may drift and that the galvanometer relay reacts to shock and building vibration.

The above problem has been satisfactorily dealt with by BTL workers under Contract OEMsr-1098, who have developed, for spectrographic use, a thermistor bolometer and an electronic amplifier for spectroscopic recording purposes. This work is described in their final report.[25]

9.13.2 Description of Component Parts

Bolometer

The bolometers developed were made of thermistor material which is a semiconducting substance with a negative temperature coefficient of resistance. Essentially, two types of bolometers were developed, namely, the unbacked (also known as air-backed) and the backed units. Description and performance characteristics of these are given in considerable detail in Section 8.7. The backed units were mounted on various materials such as rock salt, quartz, and glass and had the advantage that they were more rapidly responding than the unbacked units. At higher chopping frequencies these were generally more sensitive than the unbacked units.

The dimensions of the bolometer area are, in general, about 0.2x3.0 millimeter. They are mounted in a thin cylindrical case behind a protecting window of rock salt or, in some cases, silver chloride. The resistances of these bolometers is of the order of 2.7 megohms, and the unit must therefore be regarded as a high-impedance bolometer. The unbacked units exhibit a frequency response which can be described by a time constant. These time constants are of the order of 135 milliseconds. The frequency response of the backed units is not, strictly speaking, one which can be characterized by a time constant. For the frequency interval within which they are designed to operate the response behaves as though they had a time constant of from about 3 to 6 milliseconds.

Amplifier

The bolometer and a compensating strip, which may be either another thermistor strip or a metallic resistor, are made the two arms of a Wheatstone bridge. The bolometer bridge feeds into a preamplifier employing three vacuum tubes. The preamplifier, in turn, feeds into the main amplifier which contains a twin-T network tuned to 15 c. This part of the amplifier contains three stages of amplification. Following the amplifier is a rectifying system which furnishes a d-c current which may be used to operate a recording milliammeter. When radiation falls on the bolometer its resistance changes and the balance of the bridge is disturbed. It is the unbalance of the bolometer bridge which is amplified, rectified, and ultimately recorded.

9.13.3 Performance

The BTL detector developed for spectroscopic recording has been tested at the University of Michigan and its performance is reported in two NDRC reports.[26,27] It may be stated in a general way that for industrial infrared spectrophotometry the SETT detector is satisfactory. Its performance, while not entirely as sensitive, is comparable to that of a thermocouple and galvanometer relay. It is found that it will detect a signal of about 0.004 μw above the noise of the detecting system. The SETT device has the definite advantage over a thermocouple and galvanometer relay system that it is virtually drift-free and that its time of response is much shorter.

In certain regions of the spectrum the thermistor material transmits rather than absorbs the radiant energy falling upon it. In such regions the device is not so sensitive as would be desirable. This defect might, of course, be remedied if a blacking material could be applied which would not essentially alter the resistance of the BTL bolometer.

APPENDIX

NOTES ON GENERALIZED PHOTOMETRY, WITH PARTICULAR APPLICATION TO THE NEAR INFRARED [a]

Revised Schematic Version

By *G. A. Van Lear, Jr.*

Foreword

The following sections present the near-infrared nomenclature and units approved and recommended by the Combined NAN Committee of the C.C.B. on June 10, 1943.

The formulation so approved culminates developments represented while in progress by NDRC Reports 16.4–5 (OSRD No. 1384), and contributed to by numerous British and American scientists working in the field. While Report 16.4–9 is hereby superseded, Chapters I and II of Report 16.4–5 may be found useful in elaboration. Chapters III and IV of that report should be disregarded, particularly because of an essential difference in the infralumen as defined there and here.

Symbols Not Defined in Tables I, II

(Generally following *Illuminating Engineering Nomenclature and Photometric Standards*, Illuminating Engineering Society, 51 Madison Ave., New York, 1942.)

- E Illumination
- F Luminous flux (lumens)
- H Irradiancy, i.e., incident radiant flux per unit area (watt/cm^2)
- H_λ Spectral irradiancy, i.e., incident spectral radiant flux per unit area (watt/cm^2 per micron)
- k_λ Relative luminosity factor
- λ Wavelength (microns)
- Φ Radiant flux, i.e., radiant power (watts)
- Φ_λ Spectral radiant flux (watts per micron)

[a] NDRC Report 16.4-10 (OSRD No. 1585) under NDRC Contract NDCrc-185 with University of Michigan, Ann Arbor, Michigan.

TABLE I. Detectors, receivers, and sources.

Rate *detectors* by their *noise infrathresholds,* in mile-infracandles and/or micro-infralumens.
Rate *receivers* by their *operational infrathresholds,* in mile-infracandles.
Rate *sources of filtered radiation* by their *effective infracandle powers* for each detector type.

Two related systems express radiant flux, etc., in generalized photometric terms:

Holo-system, based on complete tungsten spectrum

Infra-system, based on infrared tungsten spectrum.

Each system is multiple-valued, recognizing the spectral response characteristics of as many different types of detectors as may be required.

Detectors are considered to be classified according to their spectral response characteristics, r_λ, for which peak value is taken as unity. Thus, all type A detectors have one spectral response characteristic; all type B detectors another, etc.

Notation follows I.E.S. Lower-case letters for unity-peak-value functions.

Quantity	Units	Discussion	Equations
Radiant flux with standard spectral distribution.	*Def*: One *hololumen* (hlm.) is that radiant flux of all wavelengths which has the spectral distribution characteristic of a tungsten lamp at color temperature 2848°K, and which, evaluated as visible light, equals one lumen.	For a tungsten lamp at 2848°K (number of hololumens) = (number of lumens). Only radiation with this *standard distribution,* designated by (°), can be expressed directly in hololumens. The hololumen is merely the unit implied in the usual manner of expressing photoelectric cell properties in terms of lumens. The holo-system will be used for expressing results when transmitted radiation and detector response both extend out of the infrared, but its principal role is that of a stepping stone.	$hF^\circ = F^\circ = 650 \int_0^\infty \Phi_\lambda{}^\circ k_\lambda d\lambda$ hololumens, (1) since (number of hololumens) = (number of lumens).
	Def: One *infralumen* (ilm.) is that portion of the hololumen which lies on the long-wave side of 0.800 μ.	For a tungsten lamp at 2848°K without filter (number of infralumens) = (number of lumens). Only radiation with this *standard distribution,* designated by (°), can be expressed directly in infralumens. The infra-system depends for its appropriateness upon the assumption that practically no radiation shorter than 0.8 μ can be tolerated. However, it is not assumed that 0.8 μ is a safe limit.	$iF^\circ = hF^\circ = F^\circ$ infralumens, (2) since (number of infralumens) = (number of hololumens).
Radiant flux with any spectral distribution.	With respect to a given type of detector, the measure of any radiant flux in *equivalent hololumens* (eq. hlm.) is the number of hololumens required to evoke the same response from such a detector.	Non-standard radiation, even if of unknown spectral distribution, can be measured in equivalent hololumens with respect to a given type of detector by an experiment involving that radiation, standard radiation, and such a detector. In case the spectral distribution of the non-standard radiation is known, Eq. (3) or Eqs. (4) and (5) will be used.	$hF' = \dfrac{650 \int_0^\infty \Phi_\lambda{}^\circ k_\lambda d\lambda}{\int_0^\infty \Phi_\lambda{}^\circ r_\lambda d\lambda} \int_0^\infty \Phi_\lambda{}' r_\lambda d\lambda$ equivalent hololumens (3) If $\Phi_\lambda{}'$ is visually appreciable, then $hF' = P \times F'$ equivalent hololumens, (4)

			where $$P = \frac{\int_0^\infty \Phi_\lambda{}^\circ k_\lambda d\lambda}{\int_0^\infty \Phi_\lambda{}^\circ r_\lambda d\lambda} \times \frac{\int_0^\infty \Phi_\lambda{}' r_\lambda d\lambda}{\int_0^\infty \Phi_\lambda{}' k_\lambda d\lambda} \qquad (5)$$ is the *effective photo-holo conversion factor*, and F' is in lumens. Also, if Φ' represents filtered radiation, so that $$\Phi_\lambda{}' = \Phi_\lambda T_\lambda, \qquad (6)$$ $$hF' = hF \times \text{ehT equivalent hololumens}, \qquad (7)$$ where ehT is the appropriate effective holotransmission of the filter (see Table 2).
Infrared flux with any spectral distribution.	*Def*: With respect to a given type of detector, the measure of any infrared flux in *equivalent infralumens* (eq. ilm.) is the number of infralumens required to evoke the same response from such a detector.	Non-standard radiation is measurable in equivalent infralumens by experiment if *either* (a) source incorporates filter passing substantially no radiation short of 0.8 μ, *or* (b) detector response to radiation short of 0.8 μ is negligible. In case the spectral distribution of the non-standard radiation is known, Eq. (8) or Eqs. (9) and (10) will be used.	Let iF' = measure of *infrared component* of spectral radiant flux $\Phi_\lambda{}'$. Then $$iF' = \frac{650 \int_0^\infty \Phi_\lambda{}^\circ k_\lambda d\lambda}{\int_{0.8\,\mu}^\infty \Phi_\lambda{}^\circ r_\lambda d\lambda} \int_{0.8\,\mu}^\infty \Phi_\lambda{}' r_\lambda d\lambda \text{ eq. ilm.} \qquad (8)$$ If $\Phi_\lambda{}'$ is visually appreciable, then $$iF' = Q \times F' \text{ equivalent infralumens}, \qquad (9)$$ where $$Q = \frac{\int_0^\infty \Phi_\lambda{}^\circ k_\lambda d\lambda}{\int_{0.8\,\mu}^\infty \Phi_\lambda{}^\circ r_\lambda d\lambda} \times \frac{\int_{0.8\,\mu}^\infty \Phi_\lambda{}' r_\lambda d\lambda}{\int_0^\infty \Phi_\lambda{}' k_\lambda d\lambda} \qquad (10)$$ is the *effective photo-infra conversion factor*, and F' is in lumens. Also, if $\Phi_\lambda{}'$ represents filtered radiation, so that $$\Phi_\lambda{}' = \Phi_\lambda T_\lambda. \qquad (6)$$ $$iF' = iF \times \text{eiT equivalent infralumens}, \qquad (11)$$ where eiT is the appropriate effective infra-transmission of the filter (see Table 2).

TABLE I. (*Continued*)

Quantity	Units	Discussion	Equations
Analogs of all photometric quantities, e.g., candlepower and illumination.	Analogs of all photometric units, based on hololumen and infralumen. Example: *One infracandle* (ic.) is the infraluminous intensity of an unfiltered 1-candlepower tungsten lamp at 2848° K color temperature.	Sources of filtered radiation for service applications will be rated in equivalent infracandles (eq. ic.) with respect to each detector of interest. Similarly, the various photometric units occurring in calculations will all be qualified as "equivalent" with respect to the detector type of interest, except when unfiltered radiation from a tungsten lamp at the standard color temperature is concerned.	
Def: The *holoresponsivity* of a detector or a complete receiver is the ratio between its response to a standard-distribution hololuminous signal and the signal magnitude, under conditions assuring linearity. For modulated signal, total swings of response and signal are used.	For receiver or detector: microvolts/mile-holocandle, . . . /mile-holocandle. Alternative for detector: volts/hololumen, . . . /hololumen.	The holoresponsivity is accessible to direct experiment, without use of any filter; this is its chief virtue. The signal radiation employed in measuring holoresponsivity need not actually have the standard distribution, provided its equivalent hololumen measure be known. In case linearity may not safely be assumed, the response-signal ratio is termed the *apparent holoresponsivity*, and conditions are specified.	$hR = \frac{\text{Response}}{hE}$ . . . /mile-holocandle (12) $= \frac{\int_0^\infty H_\lambda R_\lambda d\lambda}{hE}$. (13) Alternatively, in terms of flux, $hR' = \frac{\text{Response}}{hF}$ . . . /hololumen (12′)
Def: The *infraresponsivity* of a detector or a complete receiver is the ratio between its response to a standard-distribution infrared signal and the signal magnitude, under conditions assuring linearity. For modulated signal, total swings of response and signal are used.	For receiver or detector: microvolts/mile-infracandle, . . . /mile-infracandle. Alternative for detector: volts/infralumen, . . . /infralumen.	The infraresponsivity of a device having an appreciable fraction of its holoresponsivity short of 0.8 μ may be measured by *either* (a) using an all-infrared signal whose infraluminous measure with respect to the detector type concerned is known, *or* (b) measuring its holoresponsivity and using Eqs. (16) and (17). In case linearity may not safely be assumed, the response-signal ratio is termed the *apparent infraresponsivity*, and conditions are specified.	$iR = \frac{\text{Infrared response}}{iE}$ . . . /mile-infracandle (14) $= \int_{0.8\,\mu}^\infty H_\lambda R_\lambda d\lambda / iE$ (15) $= hR \times f,$ (16) where $f = \frac{\int_{0.8\,\mu}^\infty \Phi_\lambda {}^\circ r_\lambda d\lambda}{\int_0^\infty \Phi_\lambda {}^\circ r_\lambda d\lambda}$ (17) is the *effective holo-infra response factor*. Alternatively, in terms of flux, $iR' =$ (Infrared response)$/iF$ . . . /infralumen. (14′)

RESTRICTED

Def: The *noise* (*holo* or *infra*) *threshold* of a detector or a complete receiver, for given conditions of signal wave form, amplifier bandwith, etc., is the magnitude of the standard-distribution (hololuminous or infrared) signal which corresponds to the noise indication. The root-mean-square noise indication is used where feasible, and the total swing of a modulated signal.	For receiver or detector: mile-holocandle. Alternative for detector: micro-hololumen. For receiver or detector: mile-infracandle. Alternative for detector: micro-infralumen.	The noise (holo or infra) threshold is in effect the signal equivalent of noise. It is usually best expressed in terms of signal illumination [mile- (holo or infra) candles], even for a detector, since the angle of view obtainable in an optical system depends on surface area. Except when amplifier noise cannot be ignored, *this quantity* indicates the minimum detectable signal, subject to a multiplying factor (signal/noise ratio) depending on means of observation. A figure of merit for a detector, it is also applicable to a receiver.	If, for instance, the rms noise voltage is V_N, the noise holothreshold is given by: $hN = V_N/hR$ mile-holocandles, (18) or $hN' = 10^6\ V_N/hR'$ micro-hololumens, (18') and the noise infrathreshold by: $iN = V_N/iR = hN/f$ mile-infracandles, (19) or $iN' = 10^6\ V_N/iR' = hN'/f$ micro-hololumens (19')
Def: The *operational* (*holo* or *infra*) *threshold* of a complete receiver is the magnitude of the standard-distribution (hololuminous or infrared) signal required to give reliable operation.	mile-holocandle mile-infracandle	The operational (holo or infra) threshold is a figure of merit for a complete receiver. Its only specialized feature lies in the tungsten-lamp basis of the whole system. In this and other connections, reports on Army projects will use the *statute mile* (defined as 5280 feet), and reports on Navy projects will use the *nautical mile* (defined as 6000 feet), and will so specify in each case.	If noise is the determining factor, the operational holothreshold will be given by: $hO = n \times hN$ mile-holocandles, (20) and the operational infrathreshold by: $iO = n \times iN$ mile-infracandles, (21) where n is called the *operational factor*, and is determined by test for each particular application.

TABLE II. Filters.

Characteristic	Definition	Equations	Discussion
Spectral transmission	Fraction of energy specularly transmitted at each wavelength.	$T_\lambda = \Phi_\lambda' / \Phi_\lambda$. (22)	Basic unspecialized description of filter, from which can be calculated specialized properties defined below.
Total spectral transmission	Fraction of energy transmitted at each wavelength, including both specular and diffuse transmission.	$T_\lambda'' = \Phi_\lambda'' / \Phi_\lambda$. (22′)	
Effective (holo or infra) transmission	The *effective* (*holo* or *infra*) *transmission* of a filter, with respect to radiation of given spectral distribution and a given detector type, is the ratio Φ_0/Φ, where Φ is the (total infrared) radiant power which evokes the same detector response when directed at the detector surface through the filter as Φ_0 does with the filter absent. Φ and Φ_0 have the same spectral distribution; when this is the standard distribution, the ratio is the *standard effective* (*holo* or *infra*) *transmission* (ehT°) (eiT°). When the detector response is linear, the definition given reduces to the fractional response of the given detector type to radiation, initially of the given spectral distribution, when that radiation is passed through the filter.	For linear detectors: $\mathrm{ehT} = \dfrac{\int_0^\infty \Phi_\lambda T_\lambda r_\lambda d\lambda}{\int_0^\infty \Phi_\lambda r_\lambda d\lambda}$. (23) $\mathrm{eiT} = \dfrac{\int_{0.8\,\mu}^\infty \Phi_\lambda T_\lambda r_\lambda d\lambda}{\int_{0.8\,\mu}^\infty \Phi_\lambda r_\lambda d\lambda}$. (24) $= \mathrm{ehT} \times g/f$, (25) where $g = \dfrac{\int_{0.8\,\mu}^\infty \Phi_\lambda T_\lambda r_\lambda d\lambda}{\int_0^\infty \Phi_\lambda T_\lambda r_\lambda d\lambda}$, (26) which will usually be nearly unity, and where f is the effective holo-infra response factor of Table 1.	The effective holotransmission is applicable as a factor to results obtained by calculation or measurement with unfiltered radiation from given source to given detector type, and *is itself readily measured*. It is in effect the average spectral transmission of the filter, as weighted by emission and response characteristics. The effective infratransmission measures the filter's efficiency in passing infrared radiation of given initial spectral distribution as evaluated by a given detector type, being in effect the weighted average infrared spectral transmission of the filter. It is obtainable either by calculation from spectral transmission, or through experimental measurement of effective holotransmission and use of Eq. (25).

GLOSSARY

A. Absorptivity, the ratio of resistance change per watt of heat power input to resistance change per watt of electrical power input.

ACW. Average clear weather; transmission 0.6 per sea mile in NIR; 1 cm ppt H_2O per 1,000 yd in IIR.

ACW RANGE. Operational range in ACW; voice, at night, unless otherwise indicated.

ALL-ROUND SYSTEM. System with hpi and hpr widths over about 100 degrees.

BACKGROUND NOISE. Spurious erratic response produced in receiving instruments due to variation in background.

BACKGROUND SIGNAL. Spurious steady response produced in receiving instruments due to variation of background.

BARE CELL. Detector cell without optical system.

BARE SOURCE. Source alone without optical system.

BEAM CANDLEPOWER. The apparent intensity of a projector when viewed from a point such that the entire optical aperture appears bright and the illumination varies inversely as the square of the distance from the projector.

BEAM SPREADER. An optical element for imparting an angular divergence of a few degrees to a collimated incident beam.

BLACK BODY. A body which absorbs and radiates all wavelengths according to Planck's law.

BOLOMETER. Heat sensitive device depending for its sensitivity upon the change of resistance with temperature.

BREAKDOWN POTENTIAL. The steady d-c voltage required to initiate an electric discharge through a flash lamp.

BRIGHTNESS. The intensity of an element of surface divided by the area of the element projected on a plane perpendicular to the direction of the measurement.

BRILLIANCE. The concept of brightness extended to include radiation at wavelengths beyond the visible region.

BTL. Bell Telephone Laboratories.

BuAER. Bureau of Aeronautics, Navy Department.

BuSHIPS. Bureau of Ships, Navy Department.

CAM. Cloud attenuation meter.

C_b. Heat dissipation constant.

CESIUM VAPOR LAMP. A low-voltage arc lamp for the infrared similar to the sodium vapor lamp for the visible region.

CM PPT H_2O. The length of the cylinder produced if all the water vapor in a column along the absorbing path were condensed into water.

CMU. Control meter unit.

CONCENTRATED-ARC LAMP. A low-voltage arc lamp having nonvaporizing electrodes sealed in an atmosphere of inert gas, with a small, brilliantly incandescent cathode spot.

CONTINUUM. A spectrum having no discontinuities in the wavelengths at which radiation is emitted.

COSINE LAW. The law in accordance with which the brightness of a perfectly diffusing surface varies in any direction as the cosine of the angle between that direction and the normal to the surface.

CRO. Cathode-ray oscilloscope.

c-w. Carrier wave.

DAYLIGHT VISIBLE RANGE. Limit range at which a large black object can be seen against white sky under given weather conditions.

Δf. Increment of frequency.

DUPLEX (OPERATION). Transmitter and receiver simultaneously operable.

EHT. Effective holotransmission (see the Appendix).

EHT°. Standard effective holotransmission with reference to radiation from a tungsten source at 2848 K color temperature, and to any specific radiation detector (see the Appendix).

ENI. Equivalent noise input.

ENTRANCE ANGLE. Solid angle within which a beam must enter the base in order for a triple mirror to have the retrodirective property.

ENTRANCE PUPIL. Effective gathering area of receiver optical system.

EQUIVALENT HOLOCANDLE. Unit of intensity in the holosystem (see the Appendix).

EVT. Effective visual fractional transmission (of a filter).

EXIT PUPIL. Effective area from which transmitter beam emerges.

F. Bridge factor.

FAR INFRARED. Radiation of wavelengths greater than 1.5 microns.

FIELD OF VIEW. Solid angle "seen" by the detector.

FIR. Far infrared.

FIRBARR. Far infrared bombsight with angular rate release.

FIRR. Far infrared rangefinder.

FLASH LAMP. A gaseous discharge lamp for producing radiation pulses rather than continuous emission.

f/NUMBER. 1/relative aperture where relative aperture is the ratio of the focal length to the diameter of the lens or mirror.

G. Heat power absorbed by heat sensitive element in watts per square centimeter.

G_f. Amplifier gain.

G_M. Maximum amplifier gain within band pass of amplifier.

GPI. Glider-position indicator.

H. Effective heat capacity of bolometer.

HCP. Holocandlepower. (See the Appendix.)

HLM. Hololumen. (See the Appendix.)

HOLO. The prefix used in the holo-system (defined in the Appendix) to denote its relation to the complete spectral emission from a tungsten lamp at color temperature 2848 K as the primary holophotometric standard.

HOLOCANDLEPOWER. (See the Appendix.)

HOLOLUMEN. (See the Appendix.)

HPI. Half-peak intensity (width of transmitter beam).

HPR. Half-peak response (width of receiver directivity pattern).

I. Current.

I_b. Bolometer current.

IIR. Intermediate infrared.

IIRR. Intermediate infrared receiver.

IMAGE TUBE. Device converting NIR image to visible image.

INTERMEDIATE INFRARED. Spectral region 1.4 to 6 microns.

IRRAD. Infrared range and direction detecting equipment.

JAPIR. Japanese infrared detecting system (see Section 5.5).

"LOCK-IN" SYSTEM. Tracking system which operates after it is once pointed toward the distant source.

MDS. Minimum detectable signal.

MENI. Minimum equivalent noise input; heat signal necessary to produce rms voltage equal to rms Johnson noise of detector alone.

MESSAGE SECURITY. Freedom from interception of intelligible signals by the enemy.

MICROBEACON. Portable constant source emitting faint coded light for testing receivers.

MICROFLASH LAMP. A flash lamp which emits radiation pulses having a duration of the order of 1 microsecond.

MICROFLUX SOURCE. A calibrated source for variable radiation signals of the order of 1 microhololumen.

MINIMUM DETECTABLE RADIANT POWER. Smallest radiant power detectable above the noise.

MINIMUM DETECTABLE SIGNAL. Smallest signal detectable above the noise.

MIT. Massachusetts Institute of Technology.

MODULATION EFFICIENCY. Ratio of maximum useful crest-to-trough variation of modulated flux to average d-c flux with modulating device removed.

MODULATION RATIO. The quotient of per cent radiation modulation divided by per cent current modulation for an electrically modulated source.

NAMU. Naval Air Modifications Unit.

NARROW-ANGLE SYSTEM. System with hpi and hpr widths less than 5 degrees.

NEAR INFRARED. Primarily the spectral region comprising wavelengths between 0.8 and 1.5 microns.

NERNST GLOWER. Semiconducting incandescent electric heat source.

NIR. Near infrared.

NRL. Naval Research Laboratory.

NVR. Visual range limit of a transmitter to the dark-adapted "standard" eye (see Chapter 2) in total darkness.

ω. $2\pi \times$ frequency.

ONRD. Office of Naval Research and Development.

OPERATIONAL RANGE. Observed limit range of a communication system in field test.

OPTICS FACTOR. Ratio of maximum transmitter intensity to maximum bare source intensity; or of maximum receiver response to maximum bare cell response in field of uniform illumination.

OSU. Ohio State University (Contract OEMsr-987).

P. Power in watts.

PbS CELL. Lead sulfide photoconductive cell.

P-G SYSTEM. Plane unit, electrically modulated, of plane-to-ground communication system.

PHOTOMULTIPLIER TUBE. A combined phototube and secondary emission amplifier contained in a single evacuated glass envelope.

PIP. Signal on cathode-ray oscilloscope screen seen as a very sharp deviation from the normal signal.

PLAN-POSITION INDICATOR. An all-round signal presentation system in which target range and azimuth appear as radius and angle coordinates in a polar coordinate system centered on the screen of the cathode-ray tube.

PND. Portable infrared detector.

P-P. Plane-to-plane communication system.

PR. Plane-to-plane recognition system.

PRESS-TO-TALK BUTTON. A send-receive switch which is normally in the "receive" position.

PSD. Portable ship detector.

R. Resistance.

RADIATION DETECTOR. The element or device. e.g., phototube, bolometer, in which radiant energy is converted into electric energy.

R_b. Bolometer resistance.

RCA. RCA Victor Division of Radio Corporation of America.

RECEIVER EFFICIENCY. Ratio of flux received on detector cell to flux incident on receiver entrance pupil.

RESPONSIVITY. Response in absolute units to incident radiation in watts per square centimeter.

RETRODIRECTIVE MIRROR. See triple mirror.

RETRODIRECTIVE REFLECTOR. A reflector which redirects incident flux more or less accurately back toward its point of origin.

RMA. Radio Manufacturers' Association.

RMU. Reflector-modulator unit.

R_s. Balancing resistance.

RTL. Retrodirective target locator.

SCANNING HEAD. A unit containing the optical system of both a transmitter and a receiver, aligned with coextensive or overlapping fields of view.

SDU. Source-detector unit.

SEND-RECEIVE OPERATION. Transmitter and receiver operable only alternately.

SENSITIVITY. See responsivity.

SETT. Spectrophotometric element, type T.

SIGNAL EQUIVALENT OF NOISE. A measure of the minimum signal that can be detected by an equipment due to inherent noise limitations, more rigorously defined in the Appendix.

SINE LAW. The law in accordance with which the intensity of a linear source in any direction varies as the sine of the angle between that direction and the axis of the source.

SMOOTHING TIME. Period elapsing while filter removes fluctuations in output current of a vacuum-tube rectifier or direct-current generator.

S/N RATIO. Signal-to-noise ratio measured in decibels.

SND. Scanning infrared detector.

SONRD. Secretary, Office of Naval Research and Development.

SSD. Stabilized ship detector.

SSL. Submarine Sound Laboratory.

STABLE TABLE. Gyroscopically stabilized horizontal platform.

STANDARD EYE. Observer having red and infrared luminosity functions. (See Chapter 2.)

SYSTEM SECURITY. Freedom from interception of *any* signals by the enemy (as distinguished from message security).

T. Temperature.

t. Time constant.

TF Cell. Thallous sulfide photoconductive (Cashman) cell.

Thermistor. Semiconducting material with large negative temperature coefficient.

Threshold Flux. Minimum rms variation of flux required to give 100 per cent sentence intelligibility.

TMR. Thermal map recorder for ground survey.

Tracker System. System which automatically follows a distant radiation source.

Transceiver Head. Head containing both transmitter and receiver optical systems and associated parts.

Transmission Window. Spectral region where infrared radiation is transmitted.

Transmitter Efficiency. Ratio of flux emerging in transmitter beam to total flux emitted by source.

Triple Mirror. Triangular glass pyramid with 54–54–90° triangular faces and 60–60–60° base; a light beam entering the base from any direction within a certain entrance angle is totally reflected three times to return accurately back on its original path.

Type L. Thermal receiver with remote indicator.

Type 10. A triggered flash lamp characterized by a high peak intensity and relatively long duration of its flash.

Type 200. A triggered microflash lamp of high-peak intensity for use in ballistic photography.

Type 300. A self-breakdown microflash lamp having extremely long life at flashing rates up to 120 per second.

Vacuum Range. Maximum range of a communication system computed for conditions of no atmospheric attenuation.

V_b. Bolometer voltage.

Very Narrow Angle System. System with hpi and hpr widths less than 1 degree.

V_p. Peak value of V_b.

W. Wave form factor.

Wide-Angle System. System with hpi and hpr widths between 5 and 40 degrees.

Window. Spectral region where infrared radiation is transmitted.

Work Function. The amount of energy required to extract an electron from a given material, commonly stated in electron volts.

BIBLIOGRAPHY

Numbers such as Div. 16-302.2-M3 indicate that the document listed has been microfilmed and that its title appears in the microfilm index printed in a separate volume. For access to the index volume and to the microfilm, consult the Army or Navy agency listed on the reverse of the half-title page.

Chapter 1

1. *Notes on Generalized Photometry with Particular Application to the Near Infrared* (Revised Schematic Version), G. A. Van Lear, Jr., OSRD 1585, NDCrc-185, Report 16.4-10, University of Michigan, June 16, 1943. (Reprinted as Appendix to this volume.) Div. 16-302.2-M3
2. *Development of a Photoelastic Shutter for Modulating Infrared Light at Audiofrequencies,* Hans Mueller, OSRD 1296, OEMsr-576, MIT, Jan. 1, 1943. Div. 16-301.2-M1
3. *Development of a Photoelastic Shutter for Voice Communication over a Beam of Infrared Light,* Hans Mueller, OEMsr-576, Special Report 16.4-47 MIT, Jan. 6, 1946.
4. *Development of an Infrared Glider Position Indicator,* G. A. Van Lear, Jr., and L. N. Holland, OSRD 4752, NDCrc-185, Service Project AC-56, University of Michigan, Jan. 11, 1945. Div. 16-320.1-M2
5. *Preliminary Development and Tests of a Retrodirective Locator for the Visible and Near Infrared,* W. L. Hole, OSRD 3345, NDCrc-185, Report 16.4-22 (Report 16.4-21 included as appendix), University of Michigan, Feb. 19, 1944. Div. 16-320.2-M1
6. *A Portable Hand-Held Infrared Optical Telephone,* Harvey E. White, Alfred Einarsson, and Charles G. Miller, OSRD 6002, OEMsr-1073, Service Projects AC-226.03 and NS-371, University of California, Nov. 30, 1945. Div. 16-303.1-M2
7. *German I-R Speech Communication Apparatus Li-80,* C. V. Kent and W. L. Hole, NDCrc-185, Special Report 16.4-1, University of Michigan, Sept. 11, 1943. Div. 16-303.3-M1
8. *German Lichtsprecher 250/130,* A. H. Nethercot, Jr. and Walter S. Huxford, OSRD 6200, OEMsr-990, Service Projects SC-126, SC-128, and SC-129, Report 16.4-70, Northwestern University, Oct. 20, 1945. Div. 16-303.3-M4
9. *Japanese Light Beam Telephone, Nikko 130 and 186,* A. H. Nethercot, Jr. and Walter S. Huxford, OSRD 5763, OEMsr-990, Service Projects SC-126, SC-128, and SC-129, Report 16.4-46, Northwestern University, Aug. 1, 1945. Div. 16-303.3-M2
10. *A Photocell Test Set,* W. L. Hole and L. N. Holland, OSRD 5298, NDCrc-185, Service Projects SC-5, NS-225, and NS-151, Final Report 16.4-35 covering the period from November 1, 1943 to July 19, 1944, University of Michigan, Apr. 4, 1945. Div. 16-302.1-M1
11. *Report on an Infrared Recognition Device Developed at the University of Michigan and Demonstrated at Norfolk, Virginia, on February 12, 1943,* P. H. Geiger, J. G. Black, and E. F. Barker, OSRD 1654, NDCrc-185, Report 16.4-12, University of Michigan, Apr. 1, 1943. Div. 16-304.2-M2
12. *An Infrared Radiation System for Recognition and Ship-to-Ship Communication,* J. G. Black and P. H. Geiger, OSRD 3546, NDCrc-185, Report 16.4-23, University of Michigan, Mar. 1, 1944. Div. 16-304.1-M1
13. *A Near Infrared System for Recognition and Ship-to-Ship Communication, Type D-2,* J. G. Black, P. H. Geiger, and A. F. Fairbanks, OSRD 5993, NDCrc-185, Service Project NS-151, Final Report 16.4-59, covering period from March 1, 1944 to October 31, 1945, University of Michigan, Oct. 31, 1945. Div. 16-304.1-M2
14. *Plane-to-Plane Recognition,* P. H. Geiger and J. G. Black, OSRD 5994, NDCrc-185, Service Projects NA-194 and AC-101, Final Report 16.4-60, covering period from July 1, 1944 to October 31, 1945, University of Michigan, Nov. 1, 1945 Div. 16-304.2-M3
15. *The Development of Apparatus for the Detection of Night Bombing Planes by Near Infra-Red Radiation,* O. S. Duffendack, NDCrc-185, Engineering Research Project M-341, D-3 Progress Report 244, University of Michigan, June 1, 1942. Div. 16-304.2-M1
16. *The High Intensity Flash Lamp, Type 10, Development and Characteristics,* W. W. McCormick and L. Madansky, OSRD 1934, NDCrc-185, Report 16.4-14, University of Michigan, Aug. 24, 1943. Div. 16-301.11-M2
17. *The High Intensity Flash Lamp, Type 10,* W. L. Hole and W. W. McCormick, OSRD 5297, NDCrc-185, Final Supplementary Report 16.4-34, covering period from August 25, 1943 to March 1, 1945, University of Michigan, Oct. 1, 1945. Div. 16-301.11-M5
18. *The Microflash Lamp, Type 200, Development and Characteristics,* W. W. McCormick and L. Madansky, OSRD 1939, NDCrc-185, Report 16.4-13, University of Michigan, Aug. 21, 1943. Div. 16-301.11-M1
19. *The Type 200 Microflash Lamp and a Microflash Unit for Ballistic Photography,* W. W. McCormick and A. F. Fairbanks, OSRD 5295, NDCrc-185, Service Project OD-147, Final Report 16.4-32, covering the period from January 1, 1943 to February 28, 1945, University of Michigan, Apr. 19, 1945. Div. 16-301.11-M3
20. *A Device for Tripping the Camera Shutter in High Speed Photography,* A. F. Fairbanks, NDCrc-185, Special Report 16.4-44, University of Michigan, Nov. 1, 1945. Div. 16-301.2-M3
21. *Adaptation of the Type 10 Flash Lamp to DeBrie Camera,* A. F. Fairbanks, OSRD 5996, NDCrc-185, Service Project OD-173, Report 16.4-62, covering the period from February to September 1944, University of Michigan, Nov. 1, 1945. Div. 16-301.11-M6
22. *The Development of a Flashlamp Source for an Infrared Range and Direction Apparatus,* W. W. McCormick

and W. L. Hole, OSRD 5296, NDCrc-185, Service Projects CE-22 and NR-103, Final Report 16.4-33, covering period from October 1, 1943 to June 15, 1945, University of Michigan, Aug. 1, 1945. Div. 16-301.11-M4

22a. *Ibid.*, pp. 5-7.

23. *Concentrated-Arc Lamps*, E. C. Homer, OSRD 5300, OEMsr-984, Service Project NS-159, Final Report 16.4-43, covering period from May 12, 1943 to September 1, 1945, Western Union Telegraph Company, Aug. 31, 1945. Div. 16-301.12-M2

23a. *Ibid.*, p. 31.

24. *Infrared Voice and Code Communication Systems, Navy Type E*, Walter S. Huxford and B. J. Spence, OSRD 5999, OEMsr-990, Service Project NS-159, Final Report 16.4-65, covering the period from May 1943 to October 1945, Northwestern University, Oct. 31, 1945. Div. 16-303.2-M5

24a. *Ibid.*, pp. 15-24.

24b. *Ibid.*, pp. 93-99, 106.

24c. *Ibid.*, pp. 99-100.

24d. *Ibid.*, Appendix D., pp. 161-171.

25. *The Concentrated Arc-Lamp*, a technical bulletin issued by the Western Union Telegraph Company, Water Mill Laboratory, Water Mill, L. I., N. Y. Div. 16-301.12-M3

26. *Transmitter and Receiver Optics, Point Source Voice System*, John R. Platt, OEMsr-990, Special Report 16.4-14, Northwestern University, June 22, 1944.

27. *Theoretical Aspects of Optical Communication Systems*, Hartland S. Snyder and John R. Platt, OSRD 6289, OEMsr-990, Service Project NS-159, Report 16.4-72, Northwestern University, Oct. 31, 1945. Div. 16-303.1-M1

28. *Infrared Voice Communication Systems for Aircraft*, Everett W. Lothrop, Jr., John R. Platt, and Wallace R. Wilson, OSRD 6000, OEMsr-990, Service Projects AC-226.03 and AC-226.04, Final Report, covering the period from March 1945 to October 1945, Northwestern University, Oct. 31, 1945. Div. 16-303.2-M6

28a. *Ibid.*, pp. 17-21.

29. *Near Infrared Transmitting Filters*, R. C. Lord, OSRD 3771, NDRC Division 16, June 1, 1944. Div. 16-301.3-M2

30. *Infrared Communication System*, B. J. Spence, OSRD 6001, OEMsr-1391, Service Project NS-243, Report 16.4-67, Northwestern University, Oct. 10, 1945. Div. 16-303.3-M3

31. Report of Captain Guy Touvet to Bureau of Ships, Sections A to O inclusive, Naval Intelligence Translations, April 15, 1940 to October 17, 1945.

Chapter 2

1. *Near Infrared Transmitting Filters*, Richard C. Lord, OSRD 3771, NDRC Division 16, June 1, 1944. Div. 16-301.3-M2

1a. *Ibid.*, pp. 38-40.

2. *A Photocell Test Set*, OSRD 5298, NDCrc-185, Service Projects SC-5, NS-225, and NS-151, Final Report 16.4-35, covering period from November 1, 1943 to July 19, 1944. University of Michigan, Apr. 4, 1945. Div. 16-302.1-M1

3. *Near Infrared Filter Investigation*, Report H-2199, Naval Research Laboratory, Nov. 26, 1943.

3a. *Ibid.*, p. 18 ff.

4. *Near Infrared Filters*, Engineer Board, Corps of Engineers Report 968, Feb. 1, 1946.

4a. *Ibid.*, p. 20 ff.

5. *Filter Comparator, Visual*, Report ARL-N3/E.130, Admiralty Research Laboratory, Great Britain, Sept. 28, 1943.

6. *Range of Visibility of Infrared Sources with the Naked Eye and with Binoculars*, Carl W. Miller and Lloyd N. Beck, OSRD 5739, OEMsr-1229, Report 16.1-106, Brown University, Oct. 25, 1945. Div. 16-121.2-M1

7. *The Transmission of Radiation*, OEMsr-1085, OSRD Special Report 16.4-3, Polaroid Corporation, November 1943. Div. 16-301.3-M1

8. *The Transmission of Radiation, Report No. 2*, OEMsr-1085, OSRD Special Report 16.4-4, Polaroid Corporation, November 1943. Div. 16-301.3-M1

9. *Transmission of Radiation*, OEMsr-1085, OSRD Special Report 16.4-27, Polaroid Corporation. Div. 16-301.3-M1

10. *Infrared Filters and Their Applications*, OSRD 4098, OEMsr-987, Ohio State University, January 1 to August 1, 1944.

11. *Manufacture and Inspection of Infrared Filters*, OSRD 4950, OEMsr-987, Ohio State University, Mar. 23, 1945.

12. *Development of Infrared Plastic Filters—Final*, OSRD 5565, OEMsr-987, Ohio State University, Aug. 31, 1945.

12a. *Ibid.*, p. 15 and Fig. 14.

12b. *Ibid.*, p. 10.

13. *Improved Infrared Transmitting Filters*, OSRD 5987, OEMsr-1085, Service Projects NS-155 and CE-34, Final Report 16.4-53, covering the period from August 21, 1943 to October 31, 1945. Polaroid Corporation, Oct. 31, 1945. Div. 16-301.3-M3

13a. *Ibid.*, pp. 65-100.

Chapter 3

CASHMAN THALLOUS SULFIDE CELLS[a]

1. *Development of Sensitive Thallous Sulfide Photoconductive Cells for Detection of Near Infrared Radiation*, R. J. Cashman, OSRD 1325, OEMsr-235, Report 16.4-6, Northwestern University, Mar. 17, 1943. Contains bibliography of over 170 references on all types of infrared detectors, including 25 references on thallous sulfide and related cells. Div. 16-302.11-M2

2. *Thallous Sulfide Photoconductive Cells, A Summary of*

[a] See also bibliographies of equipment using TF cells, in Chapters 4 and 5.

Service Characteristics, W. L. Hole and R. J. Cashman, OSRD 1474, NDCrc-185 and OEMsr-235, Report 16.4-7, University of Michigan and Northwestern University, Mar. 10, 1943. Div. 16-302.11-M1

3. *Development of Stable Thallous Sulfide Photoconductive Cells for Detection of Near Infrared Radiation,* R. J. Cashman, OSRD 5997, OEMsr-235, Service Projects NS-151, NS-225, and others, Report 16.4-63, covering the period from December 1941 to October 1945, Northwestern University, Oct. 31, 1945. Selected bibliography. Div. 16-302.11-M6
4. *Thallous Sulfide Photoconductive Cell,* C. W. Hewlett, J. J. Fitz Patrick, and H. T. Wrobel, OSRD 5099, OEMsr-1322, Service Project NS-225, Report 16.4-39, General Electric Company, Feb. 28, 1945. Div. 16-302.11-M3
5. *Development of Methods for Manufacturing the Type B Thalofide Cell,* Ralph W. Engstrom and Alan M. Glover, OSRD 6003, OEMsr-1486, Service Projects NS-225, SC-5, and others, Final Report 16.4-69, covering the period from April 16 to October 31, 1945, Radio Corporation of America, Oct. 31, 1945. Div. 16-302.11-M7
6. *Research on Thallous Sulfide Photoconductive Cells,* Arthur R. von Hippel, and E. S. Rittner, OSRD 4933, OEMsr-1036, Service Projects AC-101, SC-5, and others, Report 16.4-40, MIT, Laboratory for Insulation Research, April 1945. Div. 16-302.11-M5
7. "Thallous Sulfide Photoconductive Cells," Arthur R. von Hippel and others, MIT; *Journal of Chemical Physics,* Vol. 14, June 1946, Part I, 355; Part II, p. 370.
8. *The Photoelectric Mechanism of the Thallous Sulfide Photoconductive Cell,* Arthur R. von Hippel, F. G. Chesley, H. S. Denmark, P. B. Ulin, and E. S. Rittner, MIT; paper presented at the American Physical Society meeting at Cambridge, Massachusetts, April 26, 1946.
9. *A Theoretical Approach to Some Fundamental Properties of Thallous Sulfide Photoconductive Cells,* A. W. Ewald, W. L. Hole, and G. E. Uhlenbeck, NDRrc-185, Special Report 16.4-26, University of Michigan, Mar. 15, 1945. Div. 16-302.11-M4

LEAD SULFIDE PHOTOCONDUCTIVE CELLS

10. *Development of Sensitive Lead Sulfide Photoconductive Cells for Detection of Intermediate Infrared Radiation,* R. J. Cashman, OSRD 5998, OEMsr-235, Final Report 16.4-64, covering the period from January 1944 to October 1945, Northwestern University, Oct. 31, 1945. Div. 16-302.12-M1
11. *Exploratory Equipment Using the Lead Sulfide Cell for Military Detection Purposes,* R. B. Allured, J. G. Black, W. L. Hole, and T. R. Kohler, OSRD 6290, NDCrc-185, Report 16.4-73, University of Michigan, Oct. 31, 1945. Div. 16-302.12-M2
12. *Characteristics of Cooled Lead Sulfide Photoconductive Cells,* Charles L. Oxley, Naval Research Laboratory, paper presented at the Optical Society of America meeting at Cleveland, Ohio, Mar. 8, 1946.
13. *Zeiss Lead Sulfide Cells,* Field Report TLI-2, Intelligence Branch, Technical Liaison Division, 1945.
14. *German Lichtsprecher 250/130,* A. H. Nethercot, Jr., and Walter S. Huxford, OSRD 6200, OEMsr-990, Service Projects SC-126, SC-128, and SC-129, Report 16.4-70, Northwestern University, Oct. 20, 1945. Div. 16-303.3-M4

SILICON PHOTOCONDUCTIVE CELLS

15. *An Investigation of Silicon Photoconductive Cells,* G. K. Teal, OSRD 5172, OEMsr-1231, Final Report 16.4-37, covering period from October 15, 1943 to March 31, 1944, Bell Telephone Laboratories, Jan. 4, 1945. Div. 16-302.14-M1
16. *A New Bridge Photocell Employing a Photoconductive Effect in Silicon, Some Properties of High Purity Silicon,* G. K. Teal, J. R. Fisher, and A. W. Treptow, OEMsr-1231, Bell Telephone Laboratories, paper presented at the American Physical Society meeting at Cambridge, Mass., Apr. 26, 1946.
17. *The Velocity of Propagation of the Transmitted Photoeffect in Silicon Crystals,* F. C. Brown, paper presented at the American Physical Society meeting at Cambridge, Mass., Apr. 26, 1946.

SELENIUM ELECTROLYTIC CELLS

18. *Selenium Photocells,* Arthur R. von Hippel, OSRD 1326, OEMsr-561, Progress Report 16.4-2, MIT, Laboratory for Insulation Research, January 1943. Div. 16-302.13-M1
19. *A New Electrolytic Selenium Photocell,* Arthur R. von Hippel, J. H. Schulman, and E. S. Rittner, OSRD 1969, OEMsr-561, MIT, Laboratory for Insulation Research, June 10, 1943. Includes bibliography. Div. 16-302.13-M2
20. "A New Electrolytic Selenium Photocell," Arthur R. von Hippel, J. H. Schulman, and E. S. Rittner, OEMsr-561, MIT, *Journal of Applied Physics,* Vol. 17, No. 4, April 1946, p. 215.

PHOTOTUBES AND PHOTOMULTIPLIERS

21. *Special Phototubes and Circuit Developments,* H. Salinger, OSRD 4760, OEMsr-1094, Service Projects NS-159, NR-103, and CE-22, Technical Report 16.4-38, covering the period from June 15, 1943 to December 31, 1944, Farnsworth Television and Radio Corporation, Jan. 29, 1945. Div. 16-302.21-M1
22. *Special Phototubes and Circuit Developments,* H. Salinger, OSRD 5981, OEMsr-1094, Service Projects NS-159, NR-103, and CE-22, Final Report 16.4-48, covering the period from January 1, 1945 to August 31, 1945, Farnsworth Television and Radio Corporation, Sept. 26, 1945. Div. 16-302.21-M2

GENERAL

23. *A Photocell Test Set,* W. L. Hole and L. N. Holland, OSRD 5298, NDCrc-185, Service Projects SC-5, NS-225,

and NS-151, Final Report 16.4-35, covering the period from November 1, 1943 to July 19, 1944, University of Michigan, Apr. 4, 1945. Div. 16-302.1-M1

24. *Operating Instructions for Photocell Test Set,* L. N. Holland, Special Report 16.4-6, NDCrc-185, University of Michigan, Apr. 25, 1944.
25. *Operating Instructions for Microflux Source, Model 3,* W. L. Hole, NDCrc-185, Special Report 16.4-9, University of Michigan, June 9, 1944.
26. *New Photoconductive Cells,* R. J. Cashman, Northwestern University, paper presented at the Optical Society of America meeting at Cleveland, Ohio, on Mar. 8, 1946.
27. *Some Technical Developments in Light Wave Communication,* John M. Fluke and Noel E. Porter, Section 660-E Ships, paper presented at the Institute of Radio Engineers meeting in New York City, Jan. 23–26, 1946.
28. "On the Theory of the Brownian Motion II," G. E. Uhlenbeck and Ming Chen Wang, *Reviews of Modern Physics,* Vol. 17, Nos. 2 and 3, April to July, 1945, p. 323.
29. "Recent Contributions to the Theory of Random Functions," N. Levinson, W. Pitts and W. F. Whitmore, *Science,* Vol. 103, No. 2670, Mar. 1, 1946, p. 283.
30. *Infrared Voice and Code Communication Systems, Navy Type E,* B. J. Spence, OSRD 5999, OEMsr-990, Service Project NS-159, Final Report 16.4-65, covering the period from May 1943 to October 1945, Northwestern University, Oct. 31, 1945. Div. 16-303.2-M5
   30a. *Ibid,* Appendix E, *Theoretical Aspects of Optical Communication Systems,* Hartland S. Snyder and John R. Platt, also issued as OSRD 6289, Report 16.4-72, Oct. 31, 1945. Div. 16-303.1-M1
   30b. *Ibid.,* Appendix G, *Noise in Photodetectors,* Hartland S. Snyder.
31. *Design Considerations for Wide-Angle Multipliers,* H. Salinger, Research Memorandum 49, Farnsworth Television and Radio Corporation, Jan. 18, 1944.
32. *The Modern Theory of Solids,* Frederick Seitz, McGraw-Hill Book Co., New York, 1940.
33. *Electronic Processes in Ionic Crystals,* N. F. Mott and R. W. Gurney, Oxford University Press, 1940.

Chapter 4

FOREIGN SYSTEMS AND AMERICAN SYSTEMS NOT DEVELOPED UNDER NDRC

1. "Neue Apparate für Lichttelephonie," H. Thirring, *Physikalische Zeitschrift,* Vol. 21, No. 3, Feb. 1, 1920, p. 67.
2. "Suggested Methods of Secret Signalling," E. Beckmann and P. Knipping, *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin,* Vol. 25, 1920, p. 443; *Science Abstracts* 24A, No. 858, 1921.
3. "Infrared Telegraphy and Telephony," T. W. Case, *Journal of the Optical Society of America,* Vol. 6, No. 4, June 1922, p. 398.
4. "American Physicists at War," I. Bernard Cohen, *American Journal of Physics,* Vol. 13, No. 5, October 1945, p. 333. Includes nonclassified bibliography.
5. "German 'Speech-on-Light' Signal System," D. Gifford, *Radio,* November 1943, p. 32.
6. *Report on German IR Speech Communication Apparatus, Li-80,* C. V. Kent and W. L. Hole, NDCrc-185, Special Report 16.4-1, University of Michigan, Sept. 11, 1943. Div. 16-303.3-M1
7. *German Lichtsprecher 250 (made by Zeiss 1942), Analysis of Transmitter Principles,* Harvey E. White, OEMsr-1073, Special Report 16.4-46, University of California, 1945.
8. *German Lichtsprecher 250/130,* A. H. Nethercot, Jr. and Walter S. Huxford, OSRD 6200, OEMsr-990, Service Projects SC-126, SC-128, and SC-129, Report 16.4-70, Northwestern University, Oct. 20, 1945. Div. 16-303.3-M1
9. *Japanese Light-Beam Telephone,* A. H. Nethercot, Jr. and Walter S. Huxford, OSRD 5763, Service Projects SC-126, SC-128, and SC-129, Report 16.4-46, Northwestern University, Aug. 1, 1945. Div. 16-303.3-M2
10. *Instructions for RCA Light Communication System, Type R-2,* Contract W-3434-sc-69, RCA Victor Division of Radio Corporation of America with Army Signal Corps, 1944.
11. *Optiphone AN/TVC-1 (XO-1),* War Department Technical Manual, TM 11-395, Jan. 27, 1945.

TYPE W

12. *A Portable Hand-Held Infrared Optical Telephone,* Harvey E. White, Alfred Einarsson, and Charles G. Miller, OSRD 6002, OEMsr-1073, Service Projects AC-226.03 and NS-371, Final Report 16.4-68, University of California, Nov. 30, 1945. Div. 16-303.1-M2

TYPE E

(formerly designated as Type N)

13. *Receiving Unit for Voice Transmission on Light Beam,* Everett W. Lothrop, Jr. and Hartland S. Snyder, OSRD 3122, OEMsr-990, Report 16.4-16, Northwestern University, Jan. 1, 1944. Div. 16-303.2-M1
14. *Modulator for 100-Watt Concentrated Arc,* B. J. Spence, OSRD 3123, OEMsr-990, Report 16.4-17, Northwestern University, Jan. 1, 1944. Div. 16-301.12-M1
15. *Transmitter and Receiver Optics: Point Source-Voice System,* John R. Platt, OEMsr-990, Special Report 16.4-14, Northwestern University, June 22, 1944.
16. *Report on Transmission Tests of Type N Equipment,* Walter S. Huxford, OEMsr-990, Special Report 16.4-19, Northwestern University, Dec. 14, 1944. Div. 16-303.2-M2
17. *Report on Tests of Type N Equipment at Ft. Miles, Lewes, Delaware, 14–18 November 1944,* M. J. Stola-

roff, File S-S67-(12)(660d), Serial 00227, Section 660d, BuShips, Dec. 5, 1944. Includes other BuShips references.

18. *Infrared Voice and Code Communication Systems, Navy Type E,* B. J. Spence, OSRD 5999, OEMsr-990, Service Project NS-159, Final Report 16.4-65, Northwestern University, Oct. 31, 1945. Div. 16-303.2-M5
    18a. *Ibid.,* p. 73 ff, pp. 106-7.
    18b. *Ibid.,* pp. 142-3.
19. *Test No. 1 on US/E-2 Nancy Equipment Manufactured by Belmont Radio Corporation,* OEMsr-990, Service Project NS-159, Special Report 16.4-41, Northwestern University, Sept. 17, 1945. Div. 16-303.2-M4
20. *Test No. 1 on US/E-1 Nancy Equipment Manufactured by Cover-Dual Signal Systems, Inc.,* OEMsr-990, Service Project NS-159, Special Report 16.4-42, Northwestern University, Nov. 15, 1945. Div. 16-303.2-M7
21. *Report on the Status of Electroacoustic Performance Qualifications for the Differential Microphone Used with Type E Equipment,* R. L. Osborn, OEMsr-990, Special Report 16.4-43, Northwestern University, Oct. 24, 1945.
22. *Detection of Navy Type E Source by German Seehund,* Walter S. Huxford, OEMsr-990, Service Projects SC-126, SC-128, and SC-129, Special Report 16.4-45, Northwestern University, Dec. 27, 1945. Div. 16-310.33-M1
23. *Theoretical Aspects of Optical Communication Systems,* Hartland S. Snyder and John R. Platt, OSRD 6289, OEMsr-990, Service Project NS-159, Northwestern University, Oct. 31, 1945. Div. 16-303.1-M1

AIRCRAFT SYSTEMS

24. *Infrared Voice Communication Systems for Aircraft,* Everett W. Lothrop, Jr., John R. Platt, and Wallace R. Wilson, OSRD 6000, OEMsr-900, Service Projects AC-226.03 and AC-226.04, Final Report 16.4-66, Northwestern University, Oct. 31, 1945. Div. 16-303.2-M6

CARRIER-WAVE SYSTEMS

25. *Infrared Communication Systems,* F. Smardo, OSRD 5373, OEMsr-1460, Final Report 16.4-45, V-M Corporation, Benton Harbor, Michigan, July 19, 1945. Div. 16-303.2-M3
26. *Infrared Communication System of Captain Guy Touvet,* B. J. Spence, OSRD 6001, OEMsr-1391, Service Project NS-243, Report 16.4-67, Northwestern University, Oct. 10, 1945. Div. 16-303.3-M3

PHOTOELASTIC SHUTTER

27. *Development of a Photoelastic Shutter for Modulating Infrared Light at Audiofrequencies,* Hans Mueller, OSRD 1296, OEMsr-576, Research Project DIC-6085, Report 16.4-1, MIT, Jan. 1, 1943. Div. 16-301.2-M1
28. *Memorandum on the Polarization Optics of the Photoelastic Shutter,* Hans Mueller, OSRD 3171, OEMsr-576, Research Project DIC-6085, Report 16.4-18, MIT, Nov. 15, 1943. Div. 16-301.2-M2
29. *Development of a Photoelastic Shutter for Voice-Communication over a Beam of Infrared Light,* Hans Mueller and others, OEMsr-576, Special Report 16.4-47, MIT, Jan. 6, 1946.
    29a. *Ibid.,* p. 6.

GENERAL

30. *Some Technical Development in Light Wave Communication,* John M. Fluke and Noel E. Porter, Section 660E, BuShips, paper given before Institute of Radio Engineers meeting in New York City, Jan. 23-26, 1946.
31. *A Method for the Computation of Threshold Range as Affected by Instrumental Thresholds and Atmospheric Attenuation,* W. L. Hole, OSRD 3345, NDCrc-185, Report 16.4-22, including as appendix Report 16.4-21, University of Michigan, Feb. 19, 1944. Div. 16-320.2-M1
32. *Preliminary Report No. 1 on Atmospheric Attenuation of Infrared Radiation,* John Strong, OEMsr-60, Special Report 16.4-31, Harvard University, May 29, 1945. Div. 16-320.2-M2
33. *Atmospheric Attenuation of Infrared Radiations,* John D. Strong, OSRD 5986, OEMsr-60, Final Report 16.4-52, Harvard University, Nov. 30, 1945. Div. 16-320.2-M4
34. "Mean Absorption and Equivalent Absorption Coefficient of a Band Spectrum," Walter M. Elsasser, *The Physical Review,* Vol. 54, No. 2, July 15, 1938, p. 126.
35. "The Absorption Laws for Gases in the Infra-Red," J. Rud Nielsen, V. Thornton, and E. Brock Dale, *Reviews of Modern Physics,* Vol. 16, Nos. 3 and 4, July to October 1944, p. 307.
36. "On a New Method of Measuring the Mean Height of the Ozone in the Atmosphere," John Strong, *Journal of the Franklin Institute,* Vol. 231, No. 2, February 1941, p. 138.
37. "Optics of Atmospheric Haze," E. O. Hulburt, *Journal of the Optical Society of America,* Vol. 31, No. 7, July 1941, p. 472.
38. "On the Relation between Visibility and the Constitution of Clouds and Fog," H. G. Houghton, *Journal of the Aeronautical Sciences,* Vol. 6, 1939, p. 408
39. *The Development of Apparatus for the Detection of Night Bombing Planes by Near Infrared Radiation,* NDCrc-185, Engineering Research Project M-341, Report D-3, 244, University of Michigan, June 1, 1942. Div. 16-304.2-M1
40. *A Near Infrared System for Recognition and Ship-to-Ship Communication, Type D-2,* J. G. Black, P. H. Geiger, and A. F. Fairbanks, OSRD 5993, NDCrc-185, Service Project NS-151, Final Report 16.4-59, University of Michigan, Oct. 31, 1945. Div. 16-304.1-M2
41. *On the Articulation Efficiency of Bands of Speech in Noise,* J. P. Egan and F. M. Wiener, OSRD 4872, Harvard University, May 1, 1945.
42. *Section 76.4 Bimonthly Summary Reports,* 1943-1946.
43. *Notes on Generalized Photometry with Particular Application to the Near Infrared* (revised schematic version), G. A. Van Lear, Jr., OSRD 1585, NDCrc-185, Report 16.4-10, University of Michigan, June 16, 1943. Div. 16-302.2-M3

Chapter 5

TYPE D

1. *Report on an Infrared Recognition Device Developed at the University of Michigan and Demonstrated at Norfolk, Virginia, on February 12, 1943*, P. H. Geiger, J. G. Black, and E. F. Barker, OSRD 1654, NDCrc-185, Report 16.4-12, University of Michigan, Apr. 1, 1943. Div. 16-304.2-M2
2. *An Infrared Radiation System for Recognition and Ship to Ship Communication*, J. G. Black and P. H. Geiger, OSRD 3546, NDCrc-185, Report 16.4-23, University of Michigan, Mar. 1, 1944. Div. 16-304.1-M1
3. *A Near Infrared System for Recognition and Ship to Ship Communication, Type D-2*, J. G. Black, P. H. Geiger, and A. F. Fairbanks, OSRD 5993, NDCrc-185, Service Project NS-151, Final Report 16.4-59, University of Michigan, Oct. 31, 1945. Div. 16-304.1-M2
4. *Report on the Tests Made on the First Emerson Type D Receiver*, P. H. Geiger, NDCrc-185, Special Report 16.4-7, University of Michigan, May 29, 1944.
5. *Report on the Tests Made on the First Crouse-Hinds Type D Beacons*, J. G. Black and Norman E. Barnett, NDCrc-185, Special Report 16.4-8, University of Michigan, June 1, 1944.
6. *Operational Tests of Type D Equipment*, Lawrence Dunkelman and Joseph Ballam, Report IV (33M) Electrical Section (660) BuShips, March 1944.
   6a. *Ibid.*, p. 14.
   6b. *Ibid.*, p. 34.
7. *Preliminary Instructions for U. S. Navy D-1 Nancy Equipment*, Navy Contract NObs 16077, RCA Manufacturing Company, Camden, N. J., 1944.
8. *Some Technical Developments in Light-Wave Communications*, John M. Fluke and Noel E. Porter, BuShips Electrical Section, Paper given before New York meeting of Institute of Radio Engineers, Jan. 23–26, 1946, *Proceedings of the Institute of Radio Engineers*, November 1946.

PLANE-TO-PLANE RECOGNITION SYSTEM

9. *Plane-to-Plane Recognition*, P. H. Geiger and J. G. Black, OSRD 5994, NDCrc-185, Service Projects NA-194 and AC-101, Final Report 16.4-60, University of Michigan, Nov. 1, 1945. Div. 16-304.2-M3

RETRODIRECTIVE TARGET LOCATOR

10. *Preliminary Development and Tests of a Retrodirective Locator for the Visible and Near Infrared* (including as appendix: *A Method for the Computation of Threshold Range as Affected by Instrumental Thresholds and Atmospheric Attenuation*, also issued as Report 16.4-21), W. L. Hole, OSRD 3343, NDCrc-186, Report 16.4-22, University of Michigan, Feb. 19, 1944. Div. 16-320.2-M1

JAPIR

11. *Japir Detection Equipment*, P. H. Geiger and J. G. Black, OSRD 5995, NDCrc-185, Service Project NA-191, Final Report 16.4-61, University of Michigan, Oct. 17, 1945. Div. 16-302.3-M1
12. *Operatory Manual for NA 191 Equipment*, P. H. Geiger, J. G. Black and T. R. Kohler, NDCrc-185, Special Report 16.4-32, University of Michigan, March 1945. Div. 16-302.3-M2
13. *JAPIR NAN Remote Indicating Receiver Installed Test for Satisfactory Operation*, Project TED PTR-31648.0, Radio Test at Naval Air Station, Patuxent River, Md., Feb. 8, 1945.

Chapter 6

1. *Night Surveying and Signalling by Infrared* [IRRAD], E. F. Kingsbury, OSRD 3211, OEMsr-766, Western Electric Company, Dec. 1, 1943.
2. *Night Surveying by Infrared* [IRRAD], R. C. Mathes, OSRD 4850, OEMsr-1267, Service Projects CE-22 and NR-103, Progress Report 16.4-36, BTL, Dec. 27, 1944. Div. 16-305.1-M1
3. *Night Surveying by Infrared* [IRRAD], R. C. Mathes, OSRD 5982, OEMsr-1267, Service Projects CE-22 and NR-103, Final Report 16.4-49, BTL, July 27, 1945. Div. 16-305.1-M2
4. *IRRAD Equipment for Night Surveying*, War Department Report 937, The Engineer Board, Corps of Engineers, U. S. Army, Fort Belvoir, Va., May 23, 1945.
5. *An Infrared Range and Direction Apparatus for Diffusely Reflecting Targets (Diffuse IRRAD)*, W. L. Hole, W. W. McCormick, and L. N. Holland, NDCrc-185, Service Projects CE-22 and NR-103, Final Special Report 16.4-21, University of Michigan, Sept. 17, 1945. Div. 16-305.2-M3

Chapter 7

1. *Development of an Infrared Glider Position Indicator*, G. A. Van Lear, Jr. and L. N. Holland, OSRD 4752, NDCrc-185, Final Report 16.4-31, University of Michigan, Jan. 11, 1945. Div. 16-320.1-M2
2. *Cloud Attenuation Studies, Mount Washington, New Hampshire*, G. A. Van Lear, Jr., OSRD 6201, NDCrc-185, Service Project AC-56, Final Report 16.4-71, University of Michigan, Oct. 25, 1945. Div. 16-320.2-M3

3. *Visibility in Meteorology,* W. E. Knowles Middleton, University of Toronto Press, 1941, p. 51.
4. "Optics of Atmospheric Haze," E. O. Hulburt, *Journal of the Optical Society of America,* Vol. 31, 1941, p. 467.
5. "Transmission of Light in the Atmosphere with Applications to Aviation," H. G. Houghton, *Journal of Aeronautical Science,* Vol. 9, 1942, p. 103.
6. *Notes on Generalized Photometry with Particular Application to the Near Infrared,* G. A. Van Lear, Jr., OSRD 1585, NDCrc-185, Report 16.4-10, University of Michigan, June 16, 1943. Div. 16-302.2-M3

Chapter 8

1. *Smithsonian Miscellaneous Collections,* Frederick E. Fowle, Smithsonian Institution of Washington, D. C., Vol. 68, No. 8, 1917.
2. *Comparative Testing of Thermal Detectors,* Harald N. Nielsen, OSRD 5992, OEMsr-1168, Service Project AN-6, Report 16.4-58, Ohio State University, Oct. 31, 1945. Div. 16-310.2-M4
2a. *Ibid.,* p. 70 ff.
3. *Improved Far Infrared Receivers and Associated Optics,* Louis Harris, OSRD 5299, OEMsr-1147, Service Projects AC-34, NS-157, and NS-161, Final Report 16.4-41, MIT, July 10, 1945. Div. 16-310.21-M2
4. *The Frequency Characteristics of Bolometers,* Charles B. Aiken, OEMsr-921, Service Project AC-36, Electro-Mechanical Research, Inc., Nov. 17, 1944. Div. 5-332-M2
5. *A Radiation Source for Testing Thermistor Bolometers, Cases 23244 and 25717,* N. Van Roosbrocsk, Report MM-45-2980-4, BTL, Aug. 30, 1945.
6. *Test Set and Test Procedure for Thermistor Bolometers, Cases 23244, 25717 and 25787,* J. B. Johnson, Report MM-45-2930-15, BTL, Aug. 22, 1945.
7. *15-Cycle Bolometer Amplifier, per ES 832 446, Case 23244,* H. R. Moore, BTL, Oct. 15, 1943.
8. "Thermocouples for the Measurement of Small Intensities of Radiations," Louis Harris, *The Physical Review,* Vol. 45, 1934, p. 635.
9. *Sputtered and Evaporated Thermopiles, and Studies of Their Films of Plastic Materials,* Louis Harris, OSRD 4415, MIT, Mar. 31, 1943.
10. *Construction of Evaporated Thermopiles,* A. Ph.D. Dissertation, A. Stockfleth, MIT, November, 1942.
11. *Bolometer and Infrared Receiver Components,* Robert Mack, John D. Strong, and Noel Jamison, OSRD 5983, OEMsr-60, Service Projects NS-121, N-108, and others, Report 16.4-47, Harvard University, Dec. 31, 1945. Div. 16-310.223-M2
12. *Development and Operating Characteristics of Thermistor Bolometers and Their Application in Infrared Devices,* J. A. Becker, Walter H. Brattain, and others, OSRD 5991, OEMsr-636, Service Projects NS-161 and AC-225.01, Final Report 16.4-57, BTL, Oct. 31, 1945. Div. 16-310.221-M7
13. *The Modern Theory of Solids,* Frederick Seitz, McGraw-Hill Book Co., 1940, pp. 65, 189.
14. *The Optical Properties of Thermistor Material in the Infrared,* A. H. Pfund, Special Report 16.4-22, Dec. 26, 1944. Div. 16-310.221-M4
15. *Useful Equations in the Design of Thermistors,* J. A. Becker and W. H. Brattain, BTL, Jan. 21, 1944.
16. *Heat Detection* (Engineering Report), Marcel Golay, Supplement ESL-52, Ohio State Research Foundation, June 1, 1943.
17. *Thermistor Bolometer and Amplifier for Infrared Spectrometers,* J. A. Becker and H. Cristensen, OSRD 3786, OEMsr-1098, Final Report 16.4-20, BTL, June 2, 1944. Div. 16-310.221-M1

Chapter 9

1. *Transmission of Infrared Radiation through Atmospheric Media,* Harald H. Nielsen and Ely E. Bell, OSRD 3799, OEMsr-1168, Progress Report 16.4-27, Ohio State University, May 31, 1944. Div. 16-310.1-M2
2. *Thermal Radiation from Targets and Backgrounds,* John D. Strong, OSRD 5372, OEMsr-60, Service Project NS-163, Technical Report 16.4-44, Harvard University, Mar. 30, 1945. Div. 16-310.1-M3
3. "Atmospheric Absorption of Infrared Solar Radiation at the Lowell Observatory," I. Arthur Adel, *Astrophysical Journal,* Vol. 89, 1939, p. 1.
4. "Study of Atmospheric Absorption and Emission in the Infrared Spectrum," John D. Strong, *Journal of the Franklin Institute,* Vol. 232, July 1941, p. 1.
5. *Atmospheric Attenuation of Infrared Radiations,* John D. Strong, OSRD 5986, OEMsr-60, Service Project AN-32, Final Report 16.4-52, Harvard University, Nov. 30, 1945. Div. 16-320.2-M4
6. *Infrared Search and Indicator Units for Drone Control Models A and B of the Type L System,* H. R. Moore, OSRD 5989, OEMsr-636, Service Project NA-172, Final Report 16.4-55, BTL, Oct. 31, 1945. Div. 16-310.221-M6
7. "The Polarization of Light at Sea," E. O. Hulburt, *Journal of the Optical Society of America,* Vol. 24, 1934, p. 35.
8. *Oceanography for Meteorologists,* H. U. Sverdrup, Prentice-Hall, Inc., New York, 1942, p. 225, Fig. 63.
9. *The Portable Infrared Detector,* J. A. Becker, W. H. Brattain, L. M. Ilgenfritz, H. R. Moore, and L. F. Stachler, OSRD, OEMsr-636, Final Report 16.4-28, BTL, May 29, 1944. Div. 16-310.311-M1
10. *Development of the SND-1,* W. H. Brattain and N. G. Wade, OSRD 5988, OEMsr-636, Service Projects CE-37 and AC-225.02, Final Report 16.4-54, BTL, Oct. 15, 1945. Div. 16-310.312-M3

11. *Report on Tests with SND for the Detection of Tanks at Fort Belvoir, Virginia, on January 14, 15 and 16, 1945,* OEMsr-636, Special Report 16.4-23, BTL, Jan. 23, 1945.
12. *Development of the Strip Map Recorder for Target Survey,* L. M. Ilgenfritz, R. W. Ketledge, P. B. Murphy, and J. T. Scott, OSRD 5990, OEMsr-636, BTL, Oct. 31, 1945. Div. 16-310.313-M2
13. *Ground Tests of Strip Map Recorder at Fort Knox, July 9-11, 1945,* L. M. Ilgenfritz, OEMsr-636, Special Report 16.4-36, BTL, Aug. 4, 1945. Div. 16-310.313-M1
14. *Airborne Tank Detection Tests with Strip Map Recorder,* L. M. Ilgenfritz, OEMsr-636, Special Report 16.4-39, BTL, Aug. 30, 1945.
15. *An Assessment of a Far Infrared Bombsight with Angular Rate Release,* S. Darlington, R. W. Buntenbach, and others, OEMsr-636, Service Project NO-258, Special Report 16.4-18, BTL, Dec. 7, 1944. Div. 16-320.3-M1
16. *The Portable Ship Detector,* PSD, OSRD 5984, OEMsr-60, Harvard University, Dec. 31, 1945. Div. 16-310.321-M1
17. *Stabilized Ship Detector,* SSD, OSRD 5985, OEMsr-60, Harvard University, Dec. 31, 1945. Div. 16-310.332-M1
18. *Bolometers and Optical Components of Infrared Receivers for Military Applications,* OSRD 5983, OEMsr-60, Harvard University, Dec. 31, 1945. Div. 16-310.223-M2
19. *Infrared Radiation from Targets LCT and LCI Employed in Trials of Ship Detectors at Cape Henlopen,* J. A. Sanderson, Report H-2249, Naval Research Laboratory, Feb. 28, 1944.
20. *Special Report on SSD Tests on the Marnell, October 22, 1944 to November 3, 1944,* N. C. Jamison, OEMsr-60, Special Report 16.4-25, Harvard University, Feb. 12, 1945. Div. 16-310.322-M2
21. *Exploratory Equipment Using the Lead-Sulphide Cell for Military Detection Purposes,* R. B. Allured, J. G. Black, W. L. Hole and T. R. Kohler, OSRD 6290, NDCrc-185, University of Michigan, Nov. 1, 1945. Div. 16-302.12-M2
22. *Development of Sensitive Lead Sulphide Photoconductive Cells,* R. J. Cashman, OSRD 5998, OEMsr-235, Northwestern University, Oct. 31, 1945. Div. 16-302.12-M1
23. *A Photocell Test Set,* L. N. Holland and W. L. Hole, OSRD 5298, NDCrc-185, Service Projects SC-5, NS-225, and NS-151, Final Report 16.4-35, University of Michigan, Apr. 4, 1945. Div. 16-302.1-M1
24. *Infrared Rangefinder,* John D. Strong, OSRD 5192, OEMsr-60, Service Project NO-183, Technical Report 16.4-42, Harvard University, Feb. 15, 1945. Div. 16-305.2-M2
25. *Thermistor Bolometer and Amplifiers for Infrared Spectrometers,* J. A. Becker and H. Christensen, OSRD 3786, OEMsr-1098, Final Report 16.4-20, BTL, June 2, 1944. Div. 16-310.221-M1
26. *An Investigation of the Comparative Merits of the Thermistor—a-c Amplifier System and the Thermocouple-Galvonometer System,* L. W. Gildart, OEMsr-1132, Special Report 16.4-24, University of Michigan, Jan. 21, 1944. Div. 16-310.23-M2
27. *Memorandum on Test of Thermistor Bolometers as Receivers for National Technical Laboratories Routine Infrared Spectrophotometer,* R. R. Brattain and O. Beeck, Shell Development Company, Emeryville, California, Jan. 4-13, 1944. Div. 6-310.23-M1

DIVISION 16

Chief

George R. Harrison

Deputy Chiefs

Paul E. Klopsteg
Richard C. Lord

Consultants

Herbert E. Ives
F. E. Tuttle

Technical Aides

H. R. Clark
J. S. Coleman
Richard C. Lord
H. K. Stephenson

Members

O. S. Duffendack
Theodore Dunham, Jr.
E. A. Eckhardt
Harvey Fletcher
W. E. Forsythe
Arthur C. Hardy
Herbert E. Ives
Paul E. Klopsteg
Brian O'Brien
F. E. Tuttle

SECTION 16.1

Chief

Theodore Dunham, Jr.

Consultants

G. W. Morey
F. L. Jones
H. F. Mark
H. F. Weaver

Technical Aides

Lillian Elveback
H. F. Weaver
S. W. McCuskey

Members

Ira S. Bowen
W. V. Houston
F. E. Wright
R. R. McMath
G. W. Morey

SECTION 16.2

Chief

Brian O'Brien

Consultants

W. R. Brode

V. K. Zworykin

Technical Aide

Chas. E. Waring

Members

W. E. Forsythe

Julian H. Webb

Harvey E. White

SECTION 16.3

Chief

Arthur C. Hardy

Consultants

Lewis Knudson
Parry H. Moon
Edward R. Schwarz

Technical Aides

S. Q. Duntley

Arthur W. Kenney

Ernest T. Larson

Members

Edwin G. Boring

L. A. Jones

F. C. Whitmore

SECTION 16.4

Chief

O. S. Duffendack

Consultants

W. L. Enfield
H. G. Houghton, Jr.
W. H. Radford

Technical Aides

H. S. Bull

James S. Owens

Winston L. Hole

Members

Alan C. Bemis
Saul Dushman
H. G. Houghton, Jr.
George A. Morton

SECTION 16.5

Chiefs

W. E. Forsythe
Herbert E. Ives

Deputy Chiefs

W. E. Forsythe
Brian O'Brien

Consultants

E. Q. Adams
A. C. Downes

Technical Aides

William Herriott

Val E. Sauerwein

John T. Remey

Members

D. W. Bronk
A. C. Hardy
Theodore Matson
A. H. Pfund
V. K. Zworykin
W. B. Rayton
A. B. Simmons
G. F. A. Stutz
Harvey E. White

Contract Number	*Name and Address of Contractor*	*Subject*
NDCrc-180	Massachusetts Institute of Technology Cambridge, Massachusetts	Far infrared homing bomb control
NDCrc-185	University of Michigan Ann Arbor, Michigan	Near infrared detection and signaling
OEMsr-60	Harvard University Cambridge, Massachusetts	Far infrared receiver and detector development
OEMsr-235	Northwestern University Evanston, Illinois	Thalofide and other photoconductive cells
OEMsr-561	Massachusetts Institute of Technology Cambridge, Massachusetts	Photocell development
OEMsr-576	Massachusetts Institute of Technology Cambridge, Massachusetts	Infrared communication with photoelastic shutter
OEMsr-610	Johns Hopkins University Baltimore, Maryland	Infrared optics
OEMsr-636	Bell Telephone Laboratories Murray Hill, New Jersey	Development of thermistor bolometer and far infrared detection equipments
OEMsr-984	Western Union Telegraph Co. Water Mill, Long Island, New York	Electrically modulated arc lamp
OEMsr-987	Ohio State University Columbus, Ohio	Infrared transmitting filter development
OEMsr-990	Northwestern University Evanston, Illinois	Infrared communication systems with electrically modulated lamps
OEMsr-1036	Massachusetts Institute of Technology Cambridge, Massachusetts	Photocell development
OEMsr-1073	University of California Berkeley, California	Mechanically modulated infrared communication system
OEMsr-1085	Polaroid Corporation Cambridge, Massachusetts	Infrared transmitting filters
OEMsr-1094	Farnsworth Television and Radio Corporation Fort Wayne, Indiana	Electron multiplier development
OEMsr-1098	Bell Telephone Laboratories New York, New York	Thermistor bolometers and circuits for spectrometers
OEMsr-1132	University of Michigan Ann Arbor, Michigan	Testing of bolometers and control circuits in spectrometers
OEMsr-1147	Massachusetts Institute of Technology Cambridge, Massachusetts	Far infrared receivers and associated optics
OEMsr-1168	Ohio State University Columbus, Ohio	Comparative testing of thermal detectors
OEMsr-1231	Bell Telephone Laboratories 120 Broadway New York, New York	Silicon photoconductive cells
OEMsr-1267	Bell Telephone Laboratories 120 Broadway New York, New York	Infrared range and direction equipment (Irrad)
OEMsr-1322	General Electric Company West Lynn, Massachusetts	Thalofide cell manufacturing development
OEMsr-1391	Northwestern University Evanston, Illinois	Modulated infrared beam communication transmitter and receiver
OEMsr-1460	V-M Corporation Benton Harbor, Michigan	Infrared communication system
OEMsr-1486	Radio Corporation of America Lancaster, Pennsylvania	Thalofide cell manufacturing development

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Office of the Executive Secretary, OSRD, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Title*
	Army Projects
AC–56	Infrared Device for Determining the Position of a Glider with Respect to a Tow Plane
AC–63	Protective Coatings for Mirrors and Prisms
AC–101	NIR Airplane System
AC–225	Infared and Light Target Seekers
AC–225.01 (supersedes AC–34)	Research and Development of Thermistors and Associated Control Circuits for Use in Heat Responsive, Target Seeking, Controllable Bombs
AC–225.02 (supersedes AC–87; AC–113)	Research and Development of Thermal Receiving Systems for Installation in Aircraft for the Purpose of Conducting Ground Surveys
AC–226	Infrared Aids
AC–226.01 (supersedes AC–63)	Study of Infrared Sources and Receivers Including Associated Basic Research on Optics, etc.
AC–226.03 (supersedes SC–117)	Investigation and Development of Infrared Troop Carrier Aids
AC–226.04 (supersedes SC–117)	Investigation and Development of Infrared Aids for Communication between Bombers in Formation
AN–6	Comparative Testing of Thermal Detectors
AN–32	Investigation of Atmospheric Transmissivity Throughout the Infrared Spectrum
CE–22	Development of Irrad Equipment
CE–34	Image Forming Infrared Equipment (including IR Filters)
CE–37	Applications of Far Infrared Equipment to Ground Forces
OD–147	Lights for Photography of High Velocity Projectiles
OD–173	Adaptation of Type 10 Lamp for De Brie Camera
SC–5	Near Infrared Radiation
SC–117	NIR Communication for Night Formation Flying
SC–126	Testing of Enemy Near Infrared Signal Equipment
SC–126.3	Lichtsprecher 250
SC–126.4	Lichtsprecher 80
SC–127	Testing of Enemy Far Infrared Signal Equipment
SC–128	Testing of Enemy Signal Infrared Filters
SC–128.1	Filters for Lichtsprecher 250
SC–128.2	Filters for Lichtsprecher 80
SC–129	Testing of Enemy Signal Infrared Photocells
SC–129.1	Photocells for Lichtsprechers 250 and 80
	Navy Projects
N–108	Equipment for the Detection of Night Landing Parties
NA–172	Thermal Detector with Remote Indicator
NA–191	JAPIR Detection Equipment
NA–194	Plane-to-Plane Recognition
NO–183	Long Wavelength Infrared Range Finder
NO–258	Angular Rate Bomb Release System, Employing a Long Wavelength NAN Detecting System
NR–103	Iradar
NS–121	Infrared Locator for Installation on Submarines for Detection of Ships
NS–151	Infrared Receivers and 2 Modulated Infrared Sources
NS–155	Development of Infrared Transmitting Filters
NS–157	Development of Thermopiles with High Speeds of Response
NS–159	Development of Infrared Signalling Equipment for Use in Ship-to-Ship Communication

SERVICE PROJECT NUMBERS (*Continued*)

Service Project Number	*Title*
NS-161	Development of a High-Speed Thermistor Bolometer
NS-163	Measurement of Thermal Changes at Horizon
NS-163 (Revised)	Thermal Radiation Ship and Background Survey
NS-181	Gyrostabilized Ship Detector
NS-187	Infrared Signalling Equipment with Photoelastic Shutter for Ship-to-Ship Communication
NS-225	Thallous Sulfide Photoconductive Cells
NS-243	Development of a Voice or Morse Modulated Infrared Beam Communication Transmitter and Receiver
NS-371	Optically Modulated Voice Communication System Over Infrared or Ultraviolet Radiation Beams

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.

Absorption, infrared radiation in atmosphere, 282–283
  by organic vapors, 283
  by ozone, 282
  by water vapor, 282–283
  Lambert's law, 283
Absorption bands, glasses and plastics, 165
Absorptivity, far infrared detectors, 235–236
Agency for integration of infrared research, need for, 168, 199
Aircraft communication systems, 134–145
  developmental course, 134–135
  plane-to-ground (P–G), 135–140
  plane-to-plane (P–P), 140–145
Alkali blacks photoemission, 57
Allocation agency for infrared frequencies, need for, 168, 199
Andrew superconducting bolometer, 271–273
Angle of view theorem, 60
Antimony, electrical properties, 239–241
"Apparent holoresponsivity," 366
"Apparent infraresponsivity," 366
Aquadag, thallous sulfide cell material, 69
ASE photophone, British systems, 110
Atmospheric attenuation of infrared radiation
  absorption by organic vapors, 283
  absorption by ozone, 282
  absorption by water vapor, 282–283
  attenuation coefficient, 215–216
  fog and clouds as attenuation factor, 222–224
  Lambert's law, 283
  operation range dependent on attenuation, 215–216
  scattering by fogs, 283
  ship-fired smokes, 285–286
  summary, 281–282
  "window" in atmosphere, 282–283
Atmospheric attenuation of infrared radiation, measurement, 283–286
  attenuated response curves compared with envelope curves, 285
  bolometer, 283
  envelope of initial radiation, 284
  gaseous screens, 286
  recording system, 283–284
  solar bologram, 285
  source lamp, 283
  spectrometer, 283
Atmospheric transmission, intermediate infrared region
  compared with near and far infrared transmission, 165
  haze losses, 165
  Lambert's law, violation of, 164–165
  measurement methods, 164
  transmission through smoke, 165
  water vapor transmission, 164
Atmospheric transmission, limitation of wavelength region, 44
Atmospheric transmission window, 226
Attenuation of infrared radiation by atmosphere
  see Atmospheric attenuation of infrared radiation

Background noise and signals
  see Thermal radiations of targets and background
Backscatter in voice-code communication systems, 104
Backscatter reduction
  compensating device of retrodirective target locator (RTL), 194–195
  plane-to-plane recognition (PR) system, 191
Bakelite resin BR-0014, bolometer cement, 253
Ballistic photography lamp
  see Microflash lamps for ballistic photography
BARB (British angular rate bombsight), 326
Beacons, incandescent tungsten, 14–18
  code transmission, 16
  coding of emitted radiation, 14–15
  radiation modulation, 16–17
  type D beacon, 14–16
  type D–2 beacon, 16–18
Beep-canceler of portable ship detector, 330
Bell Telephone Laboratories
  PND (portable infrared detector), 290–294
  SND (scanning infrared detector), 294–302
Bell Telephone Laboratories, bolometers
  characteristics summarized, 264
  compared with other detectors, 277
  physical description, 255
  resistance values, 256
  sensitivity values, 261
  spectroscopic recording use, 360–361
Birefringence in photoelastic shutter transmitter, 153–154
Bismuth, electrical properties, 239–241
"Black body" radiation, 225–226
"Black body" temperature, targets vs. background, 287–288
Blind flying system for gliders
  see GPI (glider position indicator)
Blinker code devices, German, 108
Bologram, solar, 285
Bolometers, 247–275
  Donau Gerät bolometer, 274
  Felix bolometer, 266–269
  Italian bolometer, 274–275
  metal strip (Strong) bolometers, 247–251
  PND (portable infrared detector) bolometer, 291
  Polaroid evaporated bolometer, 269–270
  RCA bolometer, 270–271
  responsivity, methods of specifying, 228
  Strong bolometers, 247–251
  summary, 229
  superconducting bolometer, 271–273.
  thermistor bolometers, 251–265
Bolometers, output prediction, 233–234
  bridge factor, 234
  frequency factor, 233
  general response equation, 234
  voltage dependence on circuit, 234
  waveform factor, 234
Bombsight, British BARB, 326
Bombsight with angular rate release (FIRBARR), 326–328
Brownian noise in infrared detectors, 229

CAM (cloud attenuation meter)
  see Cloud attenuation meter (CAM)
Cameras for thermal receiver, 321
Carbon dioxide absorption band in atmosphere, 282
Carbonyl process, bolometer construction, 249

Carrier-wave communication systems, 145–161
polarization systems, 150–161
Signal Corps optiphone, 145
Touvet system, 146–150
types of signals, 145
V-M Corporation system, 145
Case
thalofide cells, 61–62
World War I voice system, 109
Cashman
lead sulfide evaporation, 83
semiconductors, 63
Cashman thallous sulfide cells
see TF (thallous sulfide) cells
"Caspar" equipment, 290–345
PND (portable infrared detector), 292–294
PSD (portable ship detector), 328–332
SXD (scanning infrared detector), 294–302
SSD (stabilized ship detector), 332–345
summary, 5–6
thermal receiver with remote indicator, 313–326
TMR (thermal map recorder), 302–313
Cellulose nitrate, thermopile film, 241–242
Cesium vapor lamp, 38–43
design and construction, 38–39
dynamic impedance, 39
electrical characteristics, 38–40
infrared filters, 42–43
life test data, 41
modulation ratio, 38
optical systems, applications, 41–42
per cent current modulation, 41
starting circuits, 39–40
total flux, 41
volt-ampere curve, 39
Cesium vapor lamp, communications use
compared with concentrated arc lamp, 123, 131–132
for plane-to-ground (P–G) communication system, 137
modulation, 124
operation, 123–124
operational tests, 131–132
Cesium vapor lamp, radiation characteristics, 40–43
chT values of filters, 40, 42–43
spectral energy distribution, 40–41
total flux, 40
visual intensity, 40–41
Cloud attenuation meter (CAM), 220–224
atmospheric attenuation, 215–216
attenuation caused by fog, 222
attenuation coefficient measurement, sources of error, 223–224
clouds, effect on attenuation, 223–224
conclusions and recommendations, 224
control-meter unit, 222
field tests, 223
operational theory, 222–223
reflector-modulator unit, 222
source detector unit, 220–222
threshold contrast, 215–216
visual range, 215–216
visual range, correlation with attenuation coefficient, 223–224
Coaxial shutter, mechanical coding use, 180
Coblentz thermopile, radiation source, 237–238
Code and identification system type D, 172–189
90-cycle frequency, 179
compared with ship-to-ship system, 178–179, 188–189
daylight signaling, 187
design, 173–178
developmental phases, 172–173
laboratory type D, 174–176
laboratory type D–2, 175–176
operational tests, 187
optimum code and scanning speeds, 187
range, 178
receiver, 184–186
recommendations for future development, 188–189
security, 178
ship-to-plane recognition system, 173–174
transmitter, 180–184
Code and recognition communication systems, 170–199
beacons, 14–18
code and identification system type D, 172–189
Japanese infrared detection (JAPIR) system, 196–198
military applications, 171–172
modulation requirements, coding vs. voice communication, 170–171
mutual interference between systems, 199
plane-to-plane (P-P) system, 189–192
Polaroid Corporation type P system, 172
recommendations for future development, 198–199
retrodirective target locator (RTL), 192–195
Code and voice communication systems
see Voice-code communication systems
Communication system type L, 150–151
Communication system type W
see Telephone, infrared optical
Communication systems
see Code and recognition communication systems; Voice-code communication systems
Communication systems, vibrating mirror, 110–117
German lichtsprechers, 111–112
Japanese light-beam telephone, 111
optical telephone, type W, 112–117
RCA type R–2 unit, 110–111
Communication systems with electrical modulation, 117–145
aircraft systems, 134–135
plane-to-ground (P–G) system, 134–140
plane-to-plane (P–P) system, 140–145
ship-to-ship system, 118–140
Western Union aural signal unit, 117
Concentrated-arc lamp, 26–38
applications, 26–27
cathode spot, 27–29, 31–32
design and construction, 27–29
chT values of filters, 37
infrared filters, 37
lamp life, 31–32
lamp lives when modulated, 36
operating data, 27
radiant efficiency, 32
research recommendations, 38
spectral distribution, 32–33
static radiation characteristics, 31–33
summary, 37–38, 43
wide-beam optical system applications, 36–37
Concentrated-arc lamp, communications use, 122–124
characteristics, 123
compared with cesium vapor lamp, 123, 131–132
modulation, 124
night operations tests, 130–131
operation, 123–124
Concentrated-arc lamp, electrical characteristics, 29–31, 33–34
dynamic characteristics, 33–34

impedance, 33
modulating circuits, 33–34
operating circuits, 31
starting circuits, 30–31
volt-ampere characteristic, 29–30
Concentrated-arc lamp, modulated radiation, 34–36
distortion, 36
modulation characteristics, 34–35
modulation ratio, 35–36
per cent modulation, emitted radiation, 36
radiation components, 34
spectral distribution, radiation, 35
Corning glass nacelle filters, 190

"D" communication system
see Code and identification system type D
Daylight visible range, communication systems, 100
D-c responsivity of thermopiles
Harris thermopiles, 244
measurement of thermopile output, 233
Schwarz thermopile, 246–247
Detectors (FIR), 225–278
absorptivity, 235–236
bolometers, 247–275
comparison basis for detectors, 276–277
frequency response, 234–235, 276–277
Golay heat detector, 275–276
heat radiation in FIR region, 225–226
heating and cooling curves, 234–235
military applications, 225–226
PND (portable infrared detector), 292–294
responsivity, method of specifying, 228
spectral response, 235–236
summary, 278
terminology, 364–367
window for radiation transmission, 235
zero-frequency responsivity, 277
Detectors (FIR), noise, 228–232
amplifying system noise, 230
Brownian motions of gas particles, 229
current noise, 229
effective noise bandwidth, 229
ENI (equivalent noise input), 232, 276
inherent noise, nature of, 229–230
Johnson noise, 229–230
MDS (minimum detectable signal), 231–232
mean square noise voltage, 229
MENI (minimum equivalent noise input), 231
noise output, slow vs. rapid detection, 230
"shot effect" of electron fluctuations, 229
signal noise, 228–229
Detectors (FIR), test methods, 237–239
amplifiers, 238
black body as radiation source, 237–239
Coblentz thermopile, flux density determinant, 237–238
frequency response measurements, 238–239
heat sources, 237–238
minimum detectable signal, 239
Nernst glower as radiation source, 237
"parallelogram method" of time constant determination, 238–239
radiation standard, calibrated lamp, 237
spectral response determination, 239
Detectors (NIR), 55–92
military applications, 56
photoconductive cells, 61–92
phototubes and photomultipliers, 56–61
security and infrared signaling, 56
Direction and range detecting systems
see IRRAD
Directional indication, plane-to-plane recognition (PR) system, 190
Donau Gerät bolometer, 274
"Drone" (radio-controlled aircraft) scanning device
see Thermal receiver with remote indicator
Dyes for infrared filters, 50–53
evaporation, 51
polyvinyl alcohol soluble dyes, 51
spirit soluble dyes, 53
stability, vat dyes vs. cellophane, 50–51

"E" communication system
see Ship-to-ship communication system
Effective field of view, IIR receiver, 347–348
Effective holo-infra response factor, 366
Effective hololuminous transmission (ehT)
definition and equation, 45, 368
filters, infrared, 46
filters, near infrared, 54
low evT and high ehT, 47–49
measurement devices, 46
Effective infratransmission (eiT), 368
Effective photo-holo conversion factor, 364–365
Effective photo-infra conversion factor, 365
Effective visual transmission (evT)
filters, near infrared, 46–47, 54
formula, 45
low evT and high ehT, 47–49
measurement, 47
ehT (effective holotransmission)
definition and equation, 45, 368
filters, infrared, 46
filters, near infrared, 54
low evT and high ehT, 47–49
measurement devices, 46
eiT (effective infratransmission), 368
Elac, German lead sulfide cells, 83–84
ENI (equivalent noise input)
comparison basis for detectors, 276
equations, 263–264
far infrared detectors, 230–232
Harris thermopiles, 244
Schwarz thermopiles, 247
Strong bolometers, 250–251
Eppley thermocouple, 246, 277
Equations
"black body" radiation, 225
bolometer general response, 234
effective beam candlepower, 101–102
evT (effective visual transmission), 47
range of voice-code communication systems, 99, 105
Stefan's law, 237
TF (thallous sulfide) cell response to flux, 79
thermopiles responsivity, 233
threshold flux of voice-code communication systems, 103
voltages for infrared detectors, 229
Equations, thermistor bolometers, 262–265
ENI (equivalent noise input), 263–264
final steady-state sensitivity, 264–265
MENI (minimum equivalent noise input), 263–264
temperature rise above ambient temperature, 263
thermistor resistance relation, 263
voltage output per watt incident radiation, 262–263

Equivalent hololumens, definition and equation, 364–365
Equivalent infralumens, 365
Equivalent noise input (ENI)
comparison basis for detectors, 276
equations, 263–264
far infrared detectors, 230–232
Harris thermopiles, 244
Schwarz thermopiles, 247
Strong bolometers, 250–251
Esterline-Angus recorder, 239
Evaporation of metals, thermopile construction, 239–240
evT (effective visual transmission)
filters, near infrared, 46–47, 54
formula, 45
low evT and high ehT, 47–49
measurement, 47

Fading effect in infrared transmission, 323–326
Far infrared atmospheric transmission, 165
Far infrared detectors
see Detectors (FIR)
Far infrared filters, 54
Fax recording paper, 336
Felix bolometer, 265–269
characteristics summarized, 267
compared with other detectors, 277
construction, 265–266
frequency response, 268
output voltage, 269
resistance, 265–266
spectral response, 266–267
Filament lamp communication systems, 110
Filters
far infrared communication, 54
intermediate infrared communication, 166
summary, 2–3
Filters for near infrared transmission
see Transmission filters (NIR)
FIR (far infrared) atmospheric transmission, 165
FIR (far infrared) filters, 54
FIRBARR bombsight, 326–328
Flash lamps, 18–26
early designs, 18
microflash lamp type, 21–26, 71, 105
Flash lamps, high-intensity, 19–21
beam holocandle power, 20–21
design, 19
duration of flash, 19–20
ehT value, 20–21
lamp life, 20–21
method of firing, 19
peak intensity of flash, 19–20

Fog
attenuation of infrared radiation, 222–223, 286
particle size, 283
penetration by intermediate infrared, 85
scattering of infrared radiation, 283
"Footlight effect" of ship exposed to water's radiation, 290
14PEI phototube, 59
Fractional transmission of filters, 45
Frequency allocation for infrared communication devices, 168, 199
Frequency shift coding, 183
Fresnel lenses
for code and identification system type D, 180
for incandescent tungsten beacon, 15–16

Galena, rectifying properties, 83
Gaseous discharge lamps, 18–43
cesium vapor lamp, 38–43
concentrated-arc lamps, 26–38
flash lamps, 18–26
Gases, attenuation of infrared radiation, 286
Gelatin filters, dyed, 49
German lead sulfide cells, 83–84
German thallous sulfide cells, 62
Glasses, absorption bands, 165
Glider position indicator
see GPI (glider position indicator)
Golay heat detector
compared witth other detectors, 277
construction and operation, 275–276
responsivity, 228
summary, 227–228
GPI (glider position indicator), 215–220
atmospheric attenuation, 215–216
directional vs. positional systems, 215
flight tests, 219
operation, 216–217
receiver, 218
recommendations for future development, 220
sensitivity, field test measurements, 218–219
summary, 12
transmitter, 217
visual range and attenuation, 215–216
Guided missile, illumination by flash lamp, 19

Harris thermopiles, 239–245
backing support for metals, 241
cellulose nitrate films, 241–242
d-c responsivities, 244
ENI (equivalent noise input), 244
evaporated antimony and bismuth, electrical properties, 239–241
evaporation frames, 242
evaporation method, metals, 239–240
frequency response, 244–245
physical dimensions and properties, 243
stacking and mounting, 242–243
Haze
particles, 283
penetration by intermediate infrared, 85
solar radiation scattering, 165
Heat detection
lead sulfide cells, 88–89
TF (thallous sulfide) cells, 76
use of intermediate infrared, 85
Heat radiation in far infrared region, 225–226
Heat-homing targets, airborne survey
see TMR (thermal map recorder)
Hololumen, definition and equation, 364
Hololumen systems, near infrared photometry nomenclature, 9–10
Holoresponsivity of detector or receiver, 366
Hubbert's notations on sea reflections, 289

Identification communication system type D
see Code and identification system type D
IIR (intermediate infrared)
developments summarized, 7
haze and fog penetration, 85
heat detection use, 85
security greater than near infrared, 85
IIR atmospheric transmission
compared with near infrared transmission, 165
haze losses, 165
Lambert's law, violation, 164–165
measurement methods, 164
transmission through smoke, 165
water vapor transmission, 164
IIR communication systems, 162–168
advantages and disadvantages, 162–163
atmospheric transmission in intermediate infrared region, 164–165
compared with near infrared systems, 167–168
filters, 166
gas discharge source, 166–167
interference, 167–168

lead sulfide cells as detectors, 163
mechanical modulation source, 166–167
optical elements, glass and plastic, 165
range, 167–168
transmission curves, 166
IIR filters, 53, 166
IIR photosensitive detectors
see Lead sulfide cells
IIR receiver, 347–351
amplifier, 349
compared with stabilized ship detector (SSD), 350
detecting element, 348–349
operation, 347
optical system, 347–348
personnel detection tests, 349–350
recommendations for future development, 351
scanning mechanism, 348
ship detection tests, 350
threshold sensitivity, 349
Incandescent tungsten beacons, 14–18
automatic continuous coder, 15
"break-in" by receiving operator, 16
code speed for type D–2 beacon, 18
coding of emitted radiation, 14
construction, 16–18
plane-to-plane recognition system use, 18
radiation modulation, 16–17
transmission speed for type D beacon, 14
Incandescent tungsten lamps, 11–18
communication system with photoelectric shutters, 11–12
glider position indicator, 12
infrared optical telephone, 13–14
microfilm source for photocell set, 14
modulation difficulties, 10
plane-to-plane recognition use, 18
recognition and code communication beacons, 14–18
retrodirective reflector target locator, 12–13
Infracandle (ic.), definition, 365
Infralumen, definition, 364
Infrared component, measurement, 365
Infrared frequencies, need for allocation agency, 168, 199
Infrared research, need for integrating agency, 168, 199
Infrared signaling, 56
Infraresponsivity of detector or receiver, 366
Inrush keyers, incandescent tungsten lamps, 182–183
Intermediate infrared
see IIR
IRRAD (infrared range and direction detecting), 200–214
IRRAD for diffusely reflecting targets, 211–214
atmospheric backscatter, 213
evaluation, 214
field tests, 212–214
photomultiplier tubes, 214
range of detection for ships, 213–214
receiver optical system, 212
retrodirective reflectors, 214
scanning unit, 212
ship reflectance, 213
transmitter optical system, 211–212
transmitter visual range, 214
triple mirror vs. large extended target, 211
IRRAD for retrodirective reflector targets, 200–211
a-c power supply, 209
compared with radar, 200
d-c power supply, 208–209
field tests, 209–210
final models, 210–211
recommendations for future development, 211
source, tungsten vs. mercury, 210
IRRAD for retrodirective reflector targets, components, 201–208
brightening-voltage generator, 201
cathode-ray tube and control circuits, 206–207
coincidence range circuit, 207
range index pulse, 206
range potentiometer, 208
receiving optical system, 205–206
scanning head, 201
signal amplifier, 206
start-stop range circuit, 207
sweep amplifier-inverter circuit, 207
target, 205
time-delay range circuit, 207
transmitting optical system, 203–205
Italian bolometer, 274–275
Italian photophones, 110

Japanese light-beam telephone, 111
JAPIR (Japanese infrared) detection system, 196–198
amplifier and preamplifier, 197–198
cell arrangement, 197
chopper orientation, 197
control panel, 198
design, 196–197
evaluation, 197
operational tests, 198
recommendations for future development, 198
sky light and moonlight, effect on operation, 197
summary, 172
test lamp, 198
threshold sensitivity, 197
Johnson noise
definition and summary, 281
in far infrared detectors, 229–230, 276
thallous sulfide cell, frequency response theory, 80–81

Keyer with saturable core reactor, 182–183

Lambert's law
infrared radiation absorption in atmosphere, 283
violation in intermediate infrared region, 164–165
Lamps
cesium vapor, 38–43
concentrated-arc, 26–38
filament, 110
flash, 18–26
incandescent tungsten, 11–18
Landing craft detection
portable infrared detector (PND), 294
portable ship detector (PSD), 328–332
retrodirective target locator, 171
stabilized ship detector (SSD), 336–337
Lead sulfide cells, 83–90
as motor exhaust detectors, 89
cell types, 85
construction, 86
German cells, 83–84
heat detection, 88–89
holotransmissions, 166
intermediate infrared detection, 163, 167–168
military value, 85
recommendations for future development, 90
theoretical studies, need for, 90
variables in preparation process, 89–90
Lead sulfide cells, characteristics, 86–89
daylight range estimates, 141–143
frequency response, 87–88
linearity, 88
resistance, 86
sensitivity, 163
signal-to-noise ratio, 84
signal-to-noise ratio, compared with TF cells, 86–87
spectral response, 86–87

suitability for intermediate infrared use, 84
theoretical limitations, 88
variation of noise with voltage, 87
Lead sulfide cells, receiver, 345–351
amplifier, 349
compared with stabilized ship detector (SSD), 350
detecting element, 348–349
operation, 347
optical system, 347–348
personnel detection tests, 349–350
recommendations for future development, 351
scanning mechanism, 348
ship detection tests, 350
threshold sensitivity, 349
Lichtsprecher communication systems
design ingenuity, 111–112
lead sulfide cells, 83–84
narrow-beam factor, 108
vibrator mirror systems, 111–112
Life jackets equipped with retrodirective target locator, 171
Life raft search equipment
see RTL (retrodirective target locator)

Map of heat-homing targets
see TMR (thermal map recorder)
MDS (minimum detectable signal), 231–232
Melmac plastic filter, 52–53
MENI (minimum equivalent noise input)
definition, 231
equations, 263–264
Metal strip bolometers, 247–251
compared with other detectors, 277
construction, 248–249
nickel carbonyl construction process, 249
nickel strips, production, 248
operation, 247–248
windows, 248–249
Metal strip bolometers, characteristics, 250–251
absorptivity, 250
ENI (equivalent noise input), 250–251
frequency response curve, 250
output voltages, 251
ratio of bolometer response to Coblentz response, 250
resistance, 249–250
spectral response, 250
Meteorological conditions, effect on target infrared radiation emission, 289–290
Microbeacons, test devices for voice-code communication systems, 106–107
Microflash lamps, 21–26
IRRAD components, 203–206
type 200; 21–23
type 300; 23–26
Microflash lamps for ballistic photography, 21–23
design, 21–22
duration of flash, 22
firing method, 22
lamp life, 22
microflash unit, 22
peak intensity of flash, 22
performance, 23
Microflash lamps for target detection, 23–26
design, 23–24
duration of flash, 25–26
chT values of filters, 25–26
firing method, 24–25
firing rate, 26
flashing rate, 25
lamp life, 26
peak intensity of flash, 25
Microflux source, photocell test set, 14
Minimum detectable signal (MDS), 231–232
Minimum equivalent noise input (MENI)
definition, 231
equations for computation, 263–264
Mirror communication systems, 110–117, 200–214
German Lichtsprechers, 111–112
IRRAD for diffusely reflecting targets, 211–214
IRRAD for retrodirective reflector targets, 200–211
Japanese light-beam telephone, 111
optical telephone, 112–117
RCA type R-2 unit, 110–111
Mirrors
retrodirective triple, 192
vibrating mirror for portable infrared detectors (PND), 291–292
MIT Heat Research Laboratory, bolometers
see Felix bolometer
MK23 bombsight, 326–327
Modulated filament lamp communication systems, 110
British systems, 110
Italian photophones, 110
voice modulation, disadvantage, 110
Modulated tungsten lamp, 166–167
Modulation methods
coding vs. voice requirements, 170–171
voice-code communication systems, 96–97
Modulation ratios, near infrared sources, 10–11
Moonlight, effect on operation of JAPIR detection system, 197
Motion picture
optical and sound communication medium, 109
vibrating mirror for sound-recording system, 115
Motor exhaust detection by lead sulfide cells, 89
Mt. Wilson retrodirective triple mirrors, 192

"Nancy" military equipments
GPI, 215–220
IRRAD, 200–214
JAPIR, 196–198
life raft search equipment, 192–195
recognition and code communication system, type D, 172–189
summary, 3–5
voice and code communication systems, 96–169
Navigation markers, possible use of retrodirective target locator, 171
Near infrared
see NIR
Nernst glower
absorptivity measures, 236
radiation source, 44, 237
Nickel carbonyl process, bolometer construction, 249
Nickel strips for bolometers, 248
Night bombing planes, detection by reflected infrared radiation, 62–63
Night surveying by infrared
see IRRAD (infrared range and direction detecting)
NIR (near infrared), compared with intermediate infrared, 84–85
NIR atmospheric transmission, 165
NIR detecting devices, 55–92
military applications, 56
photoconductive cells, 61–82
phototubes and photomultipliers, 56–61
security of infrared signaling, 56
NIR sources, 9–44
applications, 9
cesium vapor lamp, 38–43
comparison, 43
concentrated-arc lamp, 26–38
incandescent tungsten lamps, 11–18
microflash lamps, 21–26
modulation ratio, 10–11

nomenclature, 9–10
recommendations for future development, 43–44
summary, 1–2
Noise (holo or infra) threshold of detector or receiver, 367
Nonex, thallous sulfide cell material, 69
Normal visual range (NVR), 47
Nylon infrared filters, 51

Operational (holo or infra) threshold of receiver, 367
Optical communication transmission vs. voice transmission, 93
Optiphone, 145, 153
Ozone absorption band in atmosphere, 282

Per cent current modulation, 11
Personnel detection
lead sulfide cells, 349–350
TMR (thermal map recorder), 309
Pfund's experiments on transmission in infrared, 261
P–G communication system
see Plane-to-ground (P–G) communication system
Photocell test set
microflux source, 14
TF (thallous sulfide) testing, 72–74
Photoconductive cells, 61–82
lead sulfide cells, 83–90
photoconductive process, 78, 82–83
properties summarized, 66
recommendations for future development, 92
selenium electrolytic cells, 92
silicon cells, 90–92
TF (thallous sulfide) cells, 61–83
Photoelastic shutter communication system, 151–160
design, 151–153
developmental course, 151
evaluation, 153
monitor, 159
operational tests, 159–161
range, 153
receiver, 159
recommendations for future development, 160
security, 153
summary, 11–12
variable quarter-wave plate, 159
Photoelastic shutter communication system, transmitter, 153–159
amplitude optimum, 154
birefringence, optimum conditions for, 153–154
comparison with optiphone, 153
driving crystals, 154, 158
glass blocks, 154, 158
oscillator, 159
soldering-quartz and glass, 158–159
stripped shutter operation, 157–158
uniform shutter operation, 154–157
Photoemission from alkali blacks, 57
Photographic recordings with remote control thermal receiver, 321–323
Photographs of target areas from planes, 308
Photometry, near infrared, 9–10
Photomultipliers
see Phototubes and photomultipliers
Photophones, British, 110
Photophones, Italian, 110
Phototubes and photomultipliers, 56–61
angle-of-view study, 60
course of development, 57
IRRAD use, 205–206
noise characteristics, 57–58
optimum voltage per stage, 61
photoemission from alkali blacks, 57
recommendations for future development, 61
ship-to-ship communication system use, 126
theoretical studies, 60–61
Phototubes and photomultipliers, construction, 57–60
cesium cathode surfaces, 57–58
fluorescence reduction, 59
fourteen stage tubes, 58–59
quadrant multiplier, 60
side view tubes, 59
signal-to-noise ratio, 58
six-stage end-view multipliers, 58
ten stage tubes, 59
vacuum phototubes, 60
Photovoltaic effects of TF (thallous sulfide) cells, 76–77
Planck's equation, black body emission, 225
Plane-to-ground (P–G) communication system, 135–140
cesium vapor lamp, 137
design and construction, 135–136
directivity patterns of the optical system, 138
evaluation, 136–137
filter, 138
ground unit; *see* Telephone, infrared optical
operational tests, 138–140
range, 136
receiver, 137–138
requirements for plane and ground units, 134
ripple noise elimination, 138
security, 136
Plane-to-plane (P–P) communication system, 140–145
control panel, 143
design, 140–141
evaluation, 142–143
operational tests, 144
optical systems, 144
range, estimated, 141–143
receiver, 143–144
recommendations for future development, 144–145
security, 141–142
transmitter, 143
Plane-to-plane recognition (PR) system, 189–192
90-cycle modulation, 191
backscatter reduction, 191
design, 189–190
development, 189–190
directional indication, 190
incandescent tungsten lamp, 18
positional indication, 191
range, 190
receiver, 191–192
recommendations for future development, 192
resistance balance maintenance, 191
security, 190
transmitter, 191
Plane-to-ship identification, 189–190
Plastic filters, dyed, 50–52
evaporated filters, 51
fabrication from dyed cellophane sheet, 50
heat resistance, 50–51
nylon filters, 51
polyvinyl alcohol filters, 51
Plastics, absorption bands, 165
PND (portable infrared detector), 292–294
ambient temperature, operational limitation, 293
background compensation, 294
bolometer, 291
components, 291–292
development, 290
effect of weather on performance, 293
indicator units, 292
minimum signal, 294
operation, 292–293
optical system, 291
orientation, horizontal vs. vertical, 293
radiation accepted by apparatus, 292–293

range, 294
summary, 6, 279–280
viewing through windows, 293
Polarization communication systems, 150–161
photoelastic shutter system, 151–160
type L system, 150–151
types of systems, 150
Polarization of light, photoelastic shutter communication system, 154–158
birefringence variations, 153–154
quarter-wave plate replaced by phase difference plates, 159
stripped shutter case, 157–158
uniform polarizer case, 154–157
Polaroid Corporation
code and recognition system, type P, 172
evaporated bolometer, 269–270
Polaroid Corporation, infrared filters, 50–52
evaporated filters, 51
fabrication from dyed cellophane sheet, 50
heat resistance, 50–51
nylon filters, 51
polyvinyl alcohol filters, 51
ship-to-ship communication system use, 129
Polyvinyl alcohol (PVA) base filters, 51
Polyvinyl butyral, bolometer binder, 252
Position indicator for gliders
see GPI (glider position indicator)
P-P communication system
see Plane-to-plane (P-P) communication system
PR recognition system
see Plane-to-plane recognition (PR) system
PSD (portable ship detector), 328–332
amplifier, 330
beep-canceler, 330
bolometer bridge, 330
compared with stabilized ship detector (SSD), 332
detecting element, 329–330
detection ranges, 331
minimum detectable signal, 330–331
operation, 328
optical system, 328
power supply, 330
presentation unit, 330
scanning system, 328–329
summary, 5
PVA (polyvinyl alcohol) filters, 51

Quadrant photomultiplier, tracking equipment, 60

R-2 vibrating mirror communication system, 110–111
Radar principles, compared with IRRAD, 200
Radiation, far infrared heat, 225–226
Radiations, targets vs. background
see Thermal radiations of targets and background
Radio-controlled aircraft, scanning device
see Thermal receiver with remote indicator
Range and direction detecting systems
see IRRAD
Range equation, voice-code communication, 99, 105
Range finder (FIR), 351–360
automatic following, 352, 359–360
field tests, 357
operation, 351–353
operational tests, 359
tests on controlled target, 356–360
Range finder (FIR), components, 353–356
amplidyne control circuit, 356
amplifier circuit, 355
amplifier system, 355–356
bolometer bridge, 355
bolometers, 353–355
optical system, 353
phasemeter circuits, 355–356
presentation unit, 356
RCA bolometer, 270–271
RCA type R-2 vibrating mirror communication system, 110–111
Receiving systems (FIR), 279–361
bombsight with angular rate release (FIRBARR), 326–327
lead sulfide cell, 345–351
PND (portable infrared detector), 290–294
PSD (portable ship detector), 328–332
range finder, 351–360
SETT (spectrophotometric element), 360–361
SND (scanning infrared detector), 294–302
SSD (stabilized ship detector), 332–345
summary, 279–280
thermal receiver with remote indicator, 313–326
TMR (thermal map recorder), 302–313
Receiving systems (FIR), common aspects, 280–290

amplifiers, 281
atmospheric attenuation of infrared radiation, 282–286
detectors, 281
military applications, 279
optical systems, 281
terminology, 364–367
thermal radiations from targets and backgrounds, 286–290
Recognition communication systems
see Code and recognition communication systems
Recommendations for future development
code and recognition communication systems, 198–199
GPI (glider position indicator), 220
IRRAD for retrodirective reflector targets, 210–211
lead sulfide cell (IIR) receiver, 351
lead sulfide cells, 90
near infrared (NIR) sources, 43–44
optical telephone, infrared, 117
photoconductive cells, 92
photoelastic shutter communication system, 160
plane-to-plane (P-P) communication system, 144–145
plane-to-plane recognition (PR) system, 192
ship-to-ship communication system, 133–134
TMR (thermal map recorder), 310–313
Touvet communication system, 150
voice-code communication systems, 168
Relative spectral radiant flux of filters, 45
Relative special responsivity, 45
Retrodirective reflectors, possible IRRAD targets, 214
RMU (reflector-modulator unit) of cloud attenuation meter, 222
Rock salt window, bolometers, 250
RTL (retrodirective target locator), 192–195
applications, 171–172
backscatter compensating device, 194–195
daytime identification, 195
design, 192–194
development, 192
double attenuation feature, 194
evaluation, 194
operational tests, 195
range, 194
security, 193–194
snow and rain effect on operation, 195

[redacted]

UNCLASSIFIED

summary, 12–13
telescopic RTL, 194
triple-mirror reflectors, 192–193

Schwarz thermopile, 246–247
compared with other detectors, 277
construction, 246–247
d-c responsivity, 246–247
equivalent noise input (ENI), 247
frequency response, 247
Scofoni communication system, 145, 153
SDO (source-detector unit) of cloud attenuation meter, 220–222
Sea and sky temperatures, 289
Sea vapors, absorption of infrared radiation, 283
Selenium electrolytic cells, 92
SETT, spectrophotometric element, 360–361
Ship detection
IRRAD (infrared range and direction detecting), 200–214
PSD (portable ship detector), 328–332
SND (scanning infrared detector), 294–302
Ship-to-plane recognition system type D, 173–174
Ship-to-ship communication system, 118–140
amalgamation with identification system type D, 179, 188–189
compared with code and identification system type D, 178
developmental history, 118
evaluation, 122
interference with identification system type D, 179, 188–189
interrelations of components, 129–130
laboratory model, 118–120
production models, 121–122
range, 122
receiver, 126–127
reception of code from Touvet system, 149
recommendations for future development, 133–134
security, 122, 134
Ship-to-ship communication system, optics, 127–129
filters, 129
phototube receiver, 128–129
point source transmitter, 127
TF cell receiver, 129
vapor lamp transmitter, 127–128
Ship-to-ship communication system, tests, 130–133
cesium vapor lamp system, 131–132
code transmission, 132
concentrated arc system, 130–131
gunfire, 133
movement of ships, 132
searchlights, 133
Ship-to-ship communication system, transmitter, 122–126
amplification, 124–125
cesium vapor lamp, 123
concentrated-arc source, 122–123
lamp modulation, 124
lamp operation, 123–124
lamp starting, 124
transmitter circuits, 125–126
"Shot effect," electron emission, 229
Shutter communication system, photoelastic
see Photoelastic shutter communication system.
Signal Corps optiphone, 145, 153
Silicon cells, 90–92
construction, 91
developmental history, 90
need for further study, 92
properties, 91–92
resistance variation with temperature, 91
signal and noise responses, 91
spectral response, 91
Silver chloride, bolometer window material, 248–249
Sky light, effect on operation of JAPIR detection system, 197
Sky temperature, 289
Smoke
attenuation of infrared radiation, measurements, 285–286
effect on intermediate infrared transmission, 165
SND (scanning infrared detector), 294–302
airborne tests, 299–302
development, 294–295
operation, 295
ship detection, field tests, 299
summary, 6, 279–280
tank detection, field tests, 297–299
SND (scanning infrared detector), components, 296–297
amplifiers, 297
detecting element, 296–297
indicating unit, 297
optical system, 296
pass band in amplifier, 299
scanning mechanism, 296
Solar radiation, transmission through atmospheric water vapor, 164–165
Spectral modulation communication system, 161–162
Spectral response
far infrared detectors, 235–236
lead sulfide cells, 86–87
TF (thallous sulfide) cells, 66, 75
Spectral transmission, filters, 368
Spectrometer for recording infrared spectra, 360–361
Spectrophotometric element (SETT), 360–361
SSD (stabilized ship detector), 332–345
compared with lead sulfide cell receiver, 350
compared with portable ship detector (PSD), 332
"definite signal range," 339
military requirements, 332
operation, 332, 342
receiver responsivity increase, 339
summary, 5–6
tests, 337–345
360° unattended search, 339–342
SSD (stabilized ship detector), components, 333–336
detecting element, 334–336
fields of view, 333
final amplifier, 336
operational tests, LCI as targets, 336–337
optical system, 333
power supply unit, 335–336
preamplifier, 335
representation unit, 336
scanning mechanism, 333–334
Stefan's law, flux densities vs. temperature differences, 237
Strong bolometer, 247–251
absorptivity, 250
compared with other detectors, 277
construction, 248–249
ENI (equivalent noise input), 250–251
frequency response curve, 250
nickel carbonyl construction process, 249
nickel strips, production, 248
operation, 247–248
output voltages, 251
ratio of bolometer response to Coblentz response, 250
resistance, 249–250
spectral response, 250
windows, 248–249
Submarine equipment for ship detection.
see PSD (portable ship detector)
Sun's surface brightness, 225
Superconducting bolometer, 271–273
Survivors at sea, detection by retrodirective target locator, 171

[redacted]

Tank detection
  scanning infrared detectors (SND), 297–299
  thermal map recorder (TMR), 310
Target detection with microflash lamps, 23–26
  design, 23–24
  duration of flash, 25–26
  ehT values of filters, 25–26
  firing method, 24–25
  firing rate, 26
  flashing rate, 25
  lamp life, 26
  peak intensity of flash, 25
Target locator, retrodirective
  see RTL (retrodirective target locator)
Targets as thermal radiators
  see Thermal radiations of targets and backgrounds
Telephone, infrared optical, 112–117
  as ground unit for plane-to-ground (P-G) communication system, 135–136, 138–140
  design, 112–114
  evaluation, 114
  operational tests, 116–117
  overmodulation effect on vibrating mirror, 115
  range, 114
  receiver, 114–116
  recommendations for future development, 117
  security, 114
  specifications, 112
  summary, 13–14
  transmitter, 112–113, 115
  vibrating mirror, 115
Telephone, Japanese light-beam, 111
Teletype writer-code communication system, 172
TF (thallous sulfide) cells, 61–83
  code and identification system type D, 184
  compared with photoemissive detectors, 68–69
  daylight range estimates, 141–143
  intermediate infrared detection, 166–167
  plane-to-ground (P-G) communication system use, 135–136
  ship-to-ship communication system use, 126–127, 129
TF (thallous sulfide) cells, development, 61–65
  British cells, 62
  Case cells, 61–62
  Cashman's work, 63
  cell property studies, 63
  German cells, 62
  ideal cell characteristics, 63
  instability of early cells, 61–62
  measures of sensitivity, 61–62
  military problems leading to TF cell research, 62–63
  production history, 64–65
TF (thallous sulfide) cells, manufacture, 69–74
  Aquadag component, 69
  cell bodies ,construction, 65–66, 69
  commercial production, 71–72
  contaminating vapors, 71
  effect of impurities, 70–71
  Nonex construction, 69
  oxidation effects, 70–71
  photocell test set, 72–74
  testing procedures, 72–74
  thallous sulfide preparation, 70–71
  variables in manufacturing process, 70
TF (thallous sulfide) cells, properties, 74–77
  see also TF (thallous sulfide) cells, theory
  heat detection, 76
  linearity, 75–76
  photovoltaic effects, 76–77
  resistance, 66–68, 74–75
  secondary emission, 76–77
  signal and noise, 67, 75–76
  signal output, 67–68
  spectral response, 66, 75
  summary, 66
  threshold sensitivity, 65, 76
TF (thallous sulfide) cells, theory, 77–83
  crystal structure, 81
  excitation noise, 80
  interrelations amongst properties, 77–78
  noise-frequency relationship, 78
  phase lag, 81
  photoconductive process, 78, 82–83
  resistance, variations with temperature, 78–79
  response to single pulse, 79–80
  response to steady flux, 79
  signal and noise, frequency response, 79–81
  thermoelectric effect, 81
Thallous sulfide cells
  see TF (thallous sulfide) cells
Thermal radiations of targets and background, 286–290
  emission of targets, 287–288
  "footlight effect," 290
  measurements of target temperature, 287
  meteorological conditions, effect on emission, 289–290
  origins of background noise and signal, 288
  sea and sky background, 289
  summary, 282
  summer vs. winter signals, 289–290
  variation vs. fluctuation, 288
Thermal receiver with remote indicator, 313–326
  airborne installation, 319–321
  fading effect in infrared transmission, 323–326
  night test flights, 323
  operation, 314–315
  sensitivity, 319
  summary, 280, 313–314
  synchronous photography, targets and CRO indications, 321–323
  target approaches, photographic records, 321–323
Thermal receiver with remote indicator, components, 315–319
  amplifiers, 317–318
  bolometer changes, 318–319
  cameras, 321
  carrier frequencies, 318
  modulators for signal channels, 318
  optical system, 315
  preamplifier, 317
  presentation unit, 318
  reflector changes, 319
  scanning mechanism, 315–316
  tilt mechanism, 316
Thermistor bolometers, 251–265
  absorptivity, 261–262
  Bell Telephone Laboratory bolometers, 255
  ENI (equivalent noise input), 259–260
  final steady-state sensitivity, 264–265
  frequency response curves, 256–259
  operation, 251–252
  resistance, 255–256
  sensitivity, 259–261
  spectral response, 261–262
  voltage output, 259–261
  Western Electric amplifier, 254–255
Thermistor bolometers, construction, 252–254
  backing process, 253
  firing operation, 252
  flakes, 252–253
  housing base and mount, 253–254
  resistance material, 252
Thermistor bolometers, equations, 262–265
  ENI (equivalent noise input), 263–264
  MENI (minimum equivalent noise input), 263–264

[redacted]

UNCLASSIFIED

temperature rise above ambient temperature, 263
thermistor resistance relation, 263
voltage output per watt incident radiation, 262–263
Thermocouples, 245–246
Eppley thermocouple, 246
Weyrich vacuum thermocouple, 245–246
Thermopiles, 239–247
Harris evaporated thermopile, 239–245
output predicted from d-c responsivity, 233
responsivity, methods of specifying, 228
Schwarz thermopile, 246–247
summary, 227
Weyrich vacuum thermocouple, 245–246
Thirring communication system, 108
Thyratron-controlled inrush keyer, 182–183
TMR (thermal map recorder), 302–313
airborne tank detection tests, 310
day vs. night operation, 308
flight tests, 308–309
general description, 303–304
high vs. low altitude performance, 310–313
military applications, 302–303
personnel detection tests, 309–310
photographs of target area, 308
recommendations for future development, 310–313
scanning speed reduction, 311–313
summary, 6, 280
TMR (thermal map recorder), components, 304–308
amplifier, 306
detecting element, 305–306
indicating unit, 307–308
mirror, 304
scanning and tilt mechanism, 304–305
Touvet communication system, 146–150
design, 146
evaluation, 147
French prototype, 146
photodetector cells, 148
range, 147
receiver electronic equipment, 148
recommendations for future development, 150
security, 147
ship-to-ship system reception from Touvet source, 149
tests, 149
transmitter, 147–148
Transmission filters (NIR), 45–54
ehT determination, 46
evT determination, 46–47
filters for radiation beyond 1.4 mc, 52
future development, 53–54
high-density filter requirements, 47–49
low-density filter requirements, 49
military requirements, 47–49
Ohio State Research Foundation filters, 52–53
prewar status, 49
short wave length filters, 52–53
summary, 2–3, 54
terminology, 45–47
Transmission filters (NIR) of Polaroid Corporation, 50–52
evaporated filters, 51
fabrication from dyed cellophane sheet, 50
heat resistance, 50–51
nylon filters, 51
polyvinyl alcohol base filters, 51
Transmission "window" in atmosphere, 226
Triple-mirror reflectors, detection of
see IRRAD for retrodirective reflector targets
Tungsten lamps, incandescent
see Incandescent tungsten lamps

Vacuum phototubes, 60
Vacuum thermocouple, Weyrich, 245–246
Vapor absorption of infrared radiation, 283
V-M Corporation communication system, 145
Voice-code communication, 93–169
aircraft use, 94
compared with optical communication systems, 93
ground use, 94–96
identification and recognition, 96
near infrared region, advantages, 93–94
operational principles, 98–99
range equation, 99, 105
security, 98
ship use, 94
Voice-code communication systems, 96–169
aircraft systems, 134–145
carrier-wave systems, 145–150
electrically modulated arc systems, 117–145
intermediate infrared systems, 162–168
polarization systems, 150–161
recommendations for future development, 168
spectral modulation system, 161–162
types of systems, 96–98
vibrating mirror systems, 110–117
Voice-code communication systems, auxiliary equipment, 106–107
image tubes, 106
microbeacons, test devices, 106–107
stabilized platforms, 105–106
Voice-code communication systems, pre NDRC, 107–110
ASE photophone, British wide-angle system, 110
blinker systems, World War I, 108–109
Case code system, 108–109
German narrow-beam systems, 108
Italian photophones, 110
Lichtsprecher systems, 108
modulated filament lamp systems, 110
sound motion pictures, 109
Thirring system, 108
Voice-code communication systems, reception, 103–105
backscatter, 104
bandwidth, 103
cell area, 103–104
daylight operation, 104–105
effective threshold flux, 103
laboratory range measurements, 104
solid angle of view, 103–104
Voice-code communication systems, transmission, 99–103
atmospheric attenuation, 99–100
beam solid angle, 102
filter choice, 102–103
high efficiency factors, 101–102
laboratory measurements, 102
modulation efficiencies, 100–101
narrow-beam systems, 101–102
pass band, 101
rule for choosing source, given problem, 102

"W" communication system
see Telephone, infrared optical
Water vapor absorption band in atmosphere, 282–283
Water vapor transmission in intermediate infrared region, 164–165
Lambert's law violation, 164–165
scattering on haze, 165
solar radiation transmission, measurement methods, 164
Wavelength allocation for infrared communication devices, 168

[redacted]

Western Electric bolometer amplifier, 254–255
Western Union aural signal unit, 117
Weyrich vacuum thermocouple, 245–246, 277
"Window" in atmosphere for infrared transmission, 226
X-cut driving crystals for photoelastic shutter communication system, 158
Xenon discharge tube, near infrared source, 43
Xenon lamp, Touvet communication system source, 147
XRX polaroid filter, 50

[redacted]

UNCLASSIFIED

[redacted]

TITLE: Summary Technical Report of the National Defense Research Committee

AUTHOR(S): Duffandack, O. S.; Platt, J. R.; Lord, R. C.; and others
ORIGINATING AGENCY: Columbia Univ., War Research Div., New York, N. Y.
PUBLISHED BY: Office of Scientific Research and Development, NDRC, Div 16

ATI- 37705

REVISION (None)

ORIG. AGENCY NO. Voi-3

PUBLISHING AGENCY NO. (None)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
1946	[redacted]	U.S.	Eng.	398	photos, diagr, graphs, drwgs

ABSTRACT: [redacted]

In the study of non-image-forming infrared, the following topics are discussed: summary of developments in infrared techniques, components, and equipments; near infrared sources; near infrared transmitting filters; non-image-forming near infrared detecting devices; near infrared voice-code communication systems; near infrared recognition and code communication systems; near infrared systems for detecting range and direction; glider position indicator and cloud attenuation meter; far infrared detecting elements; and far infrared receiving systems for military applications.

DISTRIBUTION: Copies of this report obtainable from Air Documents Division; Attn: MCIDXD

DIVISION: Sciences, General (33)
SECTION: Optics (7)

SUBJECT HEADINGS: Infrared devices - Development (51905.21); Research - Summary reports (81658.95)

ATI SHEET NO.: R-33-7-12

Air Documents Division, Intelligence Department
Air Materiel Command

AIR TECHNICAL INDEX

Wright-Patterson Air Force Base
Dayton, Ohio

[redacted]

[redacted]

TITLE: Non-Image-Forming Infrared - Summary Technical Report - Division 16, NDRC, Vol. 3

AUTHOR(S) : Duffendack, O. S.; Hole, W. J.; Lord, P. C.; and others

ORIG. AGENCY : OSRD, NDRC, Div. 16, Washington, D. C.
PUBLISHED BY : (Same)

ATI- 62294
REVISION (None)
ORIG. AGENCY NO. (None)
PUBLISHING AGENCY NO. (None)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
1946	[redacted]	U.S.	English	398	photos, tables, diagrs, graphs

ABSTRACT:

The essential features of the developments for military use in the field of non-image-forming infrared equipments are discussed. The characteristics of the sources, filters, and detectors of non-image-forming systems operating in the near-infrared region are described, together with the general construction, properties, and military applications of such systems. The development and characteristics of several different kinds of thermal detectors for far-infrared radiation are outlined. The construction, characteristics, and military applications of far-infrared receiving equipment employed for uses such as detection of various objects, determination of range and direction of marine craft, thermal mapping, and guidance of heat-sensitive target-seeking missiles are discussed.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Sciences, General (33)
SECTION: Optics (7)

ATI SHEET NO.: R-33-7-49

SUBJECT HEADINGS:
Missiles - Guidance and control (62030)
Infrared detectors (51905.3)
Fil[illegible] Infrared (36564)

Central Air Documents Office
Wright-Patterson Air Force Base, Dayton, Ohio

AIR TEC[illegible] INDEX

[redacted]